EVALUATION AND OPTIMIZATION OF AN ON-BOARD WATER SPRAY FIRE SUPPRESSION SYSTEM IN AIRCRAFT

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ABSTRACT

This paper describes a series of full-scale fire tests to evaluate and develop an on-board aircraft cabin water spray system against postcrash fires. The initial system consisted of an array of nozzles, at the ceiling, which continuously discharged water throughout the cabin for 3 minutes. Several fire scenarios were examined, including a wind-driven external fuel fire adjacent to a fuselage opening and a quiescent fuel fire impinging upon an intact fuselage. Also, both narrow-body and wide-body test articles were utilized. An analysis of the hazard measurements using a fractional effective dose model indicated the water spray provided approximately 2-3 minutes of additional survival time for all but the most severe scenario tested. Additionally, a zoned water spray system was conceptualized, designed and tested under full-scale conditions in an attempt to reduce the weight penalty of water. Test results indicated that a zoned system may be designed to give more protection and improved visibility than a continuous spray system with approximately 10 percent of the water.

1. INTRODUCTION

Aircraft crash fires are almost always initiated by the ignition of spilled jet fuel. The intensity and size of a postcrash fuel fire presents a complex and severe design threat for the aircraft manufacturers and regulatory agencies responsible for fire safety in transport aircraft. Since the mid-1980's, the Federal Aviation Administration (FAA) has adopted a series of new fire safety standards to enhance postcrash fire survivability (ref. 1). The main focus has been on the improved fire performance of cabin materials. FAA full-scale fire tests have demonstrated that seat cushion fire blocking layers and low heat release panels delay the onset of flashover, providing more time for escape. In addition, it has been shown that heat resistant evacuation slides and floor proximity lighting increase the evacuation rate of passengers.

The FAA has now embarked on a program to develop and evaluate an on-board cabin water spray fire suppression system. The baseline water spray system was designed in the United Kingdom (U.K.) by Safety Aircraft and Vehicles Equipment, Ltd. (SAVE). It basically consists of a large number of small nozzles, mounted throughout the ceiling, which discharge a fine water spray with a mean droplet diameter of about 100 microns for a period of 3 minutes (ref. 2).

The FAA program is comprised of two phases (ref. 3). Phase 1 is essentially completed and was a feasibility study of the baseline SAVE system in terms of the following factors: (1) effectiveness against postcrash fires, (2) potential benefit in past accidents, and (3) adverse impact of an accidental discharge on safety of flight, passengers, and restoration to service. The Phase 1 study indicated that a water spray system is feasible. Phase 2 is underway and includes such tasks as optimization of the system to reduce weight penalty and development of requirements and specifications.

The purpose of this paper is to summarize the results of full-scale fire tests to determine the effectiveness of a continuous discharge cabin water spray system under postcrash fire conditions. In addition, test results on a zoned water spray system to minimize weight penalty are presented.

2. TEST SETUP

The test arrangement simulated a survivable aircraft crash involving fuselage exposure to an external fuel fire. The fire source was an 8- by 10-foot pan of burning jet fuel which had been shown previously to be representative of the severe thermal threat created by a large fuel spill fire. Two types of postcrash fire scenarios were evaluated. The most commonly used scenario located the fuel fire adjacent to a hole (simulated rupture) in the test fuselage the size of a Type A door opening (76 by 42 inches). A variable speed exhaust fan in the front of the fuselage created a draft inside the cabin, allowing the degree of flame penetration through the hole and the resultant severity of the fire inside the cabin to be varied. In the second type of scenario the fuel fire was adjacent to an intact fuselage, and fire penetration into the cabin occurred after penetration or burnthrough of the fuselage shell. Fairly strict control over the fuel fire conditions was maintained because the tests were conducted inside a building, assuring test repeatability.

The tests were conducted in both a narrow-body fuselage and a wide-body fuselage. The former is a surplus B-707 airplane while the latter is a 130-foot-long hybrid consisting of a 40-foot DC-10 section married to a 90-foot cylinder.

3. EFFECTIVENESS TESTS

Narrow-Body Test Article. A plan view of the narrow-body test article is shown in figure 1, indicating the SAVE water spray system nozzle arrangement and location of instrumentation and cabin materials. The water spray system consisted of 120 nozzles which discharged 72 gallons of water over a period of 3 minutes. Instrumentation consisted of thermocouples, smoke meters, gas analyzers, gas sampling equipment, calorimeters, and photo and video cameras. A 24-foot-long section of the test article, centered at the external fire pan, was outfitted with 5 rows of passenger seats, ceiling panels, stowage bins, sidewalls, and carpet. All materials were compliant with the current FAA fire test standards (ref. 1).

A zero ambient wind condition was simulated by not operating the exhaust fan. With the absence (initially) of flame penetration through the fuselage opening, the fire threat was dominated by intense thermal radiation. The results of the zero wind tests, with and without water spray, are shown in figure 2. The shaded curves in this and subsequent figures show the range in measurements at a particular fuselage station. In all cases, the highest readings were at the highest locations, and the readings decreased the closer the measurement location was to the floor. Temperature was measured at 1-foot increments from a location 7 feet high (slightly below the ceiling) to a location 1 foot above the floor. Smoke was measured at three heights: 5 feet, 6 inches; 3 feet, 6 inches; and 1 foot, 6 inches. All gas measurements were at 5 feet, 6 inches and 3 feet, 6 inches.

Figure 2 exhibits a rapid rise in temperature and toxic gas production and a decrease in oxygen concentration at approximately 5 minutes in the test without the water spray. This behavior indicates the development of a flashover condition at 5 minutes. However, when water spray was used, survivable conditions prevailed for the entire 7-minute test duration. The time interval of actual water spray discharge was from 15 seconds until approximately 195-200 seconds into the test. Therefore, in addition to the reduction in cabin fire hazards during the water spray discharge, there were notable improvements in the cabin environment after the discharge was completed.

Survival time was calculated from the measured hazards by employing a fractional effective dose (FED) model developed recently (ref. 4). The model is believed to reflect the current state-of-the-art data in terms of incapacitation of humans subjected to a single toxic combustion gas. It assumes that the effect of heat and each toxic gas on incapacitation is additive. It also assumes that the increased respiratory rate due to elevated carbon dioxide levels is manifested by the enhanced uptake of other gases. The FED plot in figure 2 shows incapacitation at 5 minutes without water spray discharge, corresponding to the time of flashover. Discharge of water spray prevented flashover within the 7-minute test duration and maintained a survivable environment within that increment (FED<0.1 at 7 minutes). Therefore, the increase in survivability provided by water spray discharge was much greater than 2 minutes.

A "moderate" wind scenario was devised, by operating the exhaust fan to induce fuel fire flame penetration through the fuselage opening, in order to create a more severe fire threat than imposed by the zero wind condition. Figure 3 shows the results of those tests. The profiles are quite similar to the zero wind test (figure 2) but are transposed earlier in time by about 2 minutes. Flashover occurred between 150 and 180 seconds without water spray. With water spray, flashover occurred much later (close to 300 seconds) and with a much lower intensity (less temperature rise and gas production). The FED plot shows that the increase in survival time was 215 seconds. Figure 3 also shows the effectiveness of water spray in removing water soluable acid gases such as hydrogen fluoride.

The water spray system was also evaluated against a "high" wind scenario. In this case, the fuel fire flames penetrated across the ceiling practically to the opposite side of the cabin. The fire was so severe that it overwhelmed the water spray, and it became necessary to terminate the test after only 60 seconds. The test illustrated that the benefits of fire safety design improvements are highly dependent upon the fire scenario, and for some scenarios, it is virtually impossible to improve survivability by design changes.

Conversely, the water spray system proved effective against the burnthrough scenario. In this case, the fire entered the cabin, at approximately 1 minute into the test, by burning through the floor and sidewall area. FED analysis indicated that 132 seconds of additional survival time was provided by the water spray system.

Wide-Body Test Article. Installed inside the wide-body test article, the SAVE system consisted of 324 nozzles arranged in 5 rows along the length of the fuselage, discharging 195 gallons of water over a period of 3 minutes. The fuel fire conditions, instrumentation, and arrangement of interior materials were similar to the narrow-body test article setup. Again, there were 5 rows of interior materials centered about the fire door, which was located at fuselage station 940 (78 feet from the front of the fuselage). Of course, the quantity of interior materials was far greater; e.g., 9 seats across/double aisle in the wide-body versus 5 seats across/single aisle in the narrow-body.

A "moderate" wind condition, causing fuel fire flame penetration through the fuselage opening, was utilized to evaluate the effectiveness of water spray in the wide-body test article. Figure 4 shows the results of those tests. As in the narrow-body tests, significant reduction in cabin temperatures and toxic gas levels were evidenced during the water spray test. Of some concern is the light transmission profiles reflecting the loss in visibility due to smoke. For more than half the test duration, because the water spray tends to lower and distribute the ceiling smoke layer, there is a greater reduction in light transmission while the water is being discharged. Apparently, the amount of smoke particulate removal or "washing out" by the water spray is more than offset by the lowering of the smoke layer. Later, however, the reduction in light transmission with an unabated fire becomes more significant.

The FED curve indicates a loss of survivability at 215 seconds without the water spray system. Examination of the temperature and gas levels, particularly oxygen concentrations (not shown), indicates the onset of flashover at about 210 seconds. With water spray, flashover was prevented over the 5-minute test duration and the cabin environment (away from the fire source) remained survivable. On the basis of the FED calculation, the improvement in survival time was 85 seconds at the end of the test (5 minutes) but would likely have been considerably longer, perhaps 2-3 minutes, had the test not been terminated.

4. SYSTEM OPTIMIZATION

Because of payload, weight penalty is an overriding consideration in aircraft design. The weight penalty associated with the SAVE system is somewhat excessive, if not prohibitive. Therefore, a zoned water spray system for the expressed purpose of weight reduction was conceptualized, designed, and tested.

The zoned concept divides an airplane into a series of water spray zones. Discharge of water within each zone is independent of the other zones and triggered by a sensor within the zone. In this manner the quantity of water discharged is dictated by the presence and spread of fire, eliminating the ineffectual and wasteful discharge of water away from the fire as in the SAVE system (ref. 5).

A zoned water spray system design has been tested in the narrow-body test article. Each zone is 8 feet in cabin length. Four spray nozzles are mounted at the cabin periphery in each of the two boundary planes, with the spray discharge directed toward the center of the zone. Specifically, each nozzle is mounted perpendicular to the supply line and at a 45° angle with the vertical traverse plane (figure 5). Testing to date has been limited to 5 zones, centered about the fire door, comprising approximately 1/3 of the cabin length. Based on preliminary tests, a temperature of 300 °F was selected to activate water discharge (manually). The temperature is measured at the centerline of the zone, about 6 inches below the ceiling. The water supply line from the storage tank is charged with water up to a separate solenoid valve connected to each zone, mounted as close as possible to the zone, in order to minimize lag times and line losses. The plumbing inside the test article is initially dry.

Since the zoned system comprised approximately 1/3 of the test article, the initial series of tests utilized 24 gallons of water (versus 72 gallons for the SAVE system). In effect, the tests were simulating a system failure causing 2/3 of the water supply to be unavailable. Three types of nozzles were evaluated: low, 0.23 gallons per minute (gpm) (SAVE nozzle); medium, 0.35 gpm; and high, 0.50 gpm. A more severe simulated wind condition than employed previously was used as a test condition (external fuel fire/fuselage opening scenario).

The calculated FED profiles from the initial series of optimization tests are shown in figure 6. The SAVE water spray system increased the survival time by 110 seconds. More importantly, the medium and high flow rate nozzles, discharging a total of only 24 gallons of water, increased the survival time beyond the SAVE system by about 55 seconds and 35 seconds, respectively. The improvement provided by the higher flow rate nozzles is apparently due to the application of larger quantities of water where it is needed most--in the immediate fire area. An interesting result is that the medium flow rate nozzles provided more protection than the high flow rate nozzles. A possible explanation is that the discharge time was longer with the medium flow rate nozzles; i.e., 180 seconds versus 140 seconds.

A second series of tests was undertaken to evaluate the impact of an even smaller supply of water. Eight gallons, or 1/9 the SAVE system total, was selected for examination. Figure 7 compares the FED profiles for the low and medium flow rate nozzles at 24 and 8 gallons of water. Figure 8 presents the temperature and carbon monoxide histories for these four tests. In figure 7 it is noteworthy that the survival time is 50 seconds greater at 8 gallons than at 24 gallons for the low flow rate nozzles. Also, the survival times are about equal for the medium flow rate nozzles for both water quantities and are greater than the low flow rate nozzles.

It is difficult to explain the longer survival time at 8 gallons, as compared to 24 gallons, for the low flow rate nozzles. Analysis of the data and the FED calculations indicate the higher levels of CO in the 24 gallon test (figure 8) and the dominant effect of CO in the FED model caused the smaller survival time. What caused the CO levels to be higher in this test is not completely clear. It may be that the longer discharge time at 24 gallons cooled and lowered the smoke layer enough to raise the CO levels at 5 feet, 6 inches. Additional tests are required to analyze these effects. What is clear and most important, however, is that relatively small quantities of water in a zoned system provide a significant improvement in survival time compared to a system that discharges water simultaneously throughout the cabin. For example, 8 gallons of water with a zoned system and medium flow rate nozzles provided a 55-second longer survival time than the SAVE system, which requires 72 gallons of water.

A zoned system test with 4 gallons of water was conducted to determine whether this relatively small quantity of water could be effective against a postcrash fire. Figure 9 compares the FED calculations for zoned system tests at 4, 8, and 24 gallons, using medium flow rate nozzles, with the baseline test without water and with the SAVE system test. Even with only 4 gallons of the water, the zoned system was effective; however, the additional escape time was less than with the zoned systems employing larger quantities of water or with the SAVE system. Nevertheless, it is impressive that such a small quantity of water can provide a finite improvement in survival time at all.

Improved visibility is another advantage of a zoned water spray system. As discussed earlier, continuously discharging water throughout the airplane tends to disrupt the concentrated smoke layer located at the ceiling and redistribute the smoke throughout the distance from the ceiling to the floor. With a zoned system the disruption of the smoke layer is primarily confined to the spray zones. Outside of the spray zones it appears that the smoke restratisfies, forming a distinct smoke layer, with improved visibility below the smoke layer. Figures 10, 11, and 12 show the light transmission measurements for selected zoned system tests compared with the baseline test without water and with the SAVE system test, at a height of 5 feet 6 inches, 3 feet 6 inches, and 1 foot 6 inches, respectively. The improvement in visibility (greater light transmission) provided by the zoned system is evident in these figures. Also, it is interesting that the amount of improvement becomes greatest at the lowest cabin heights.

A total of 9 water spray zoned tests were conducted, employing 4 water quantities and 3 nozzle flow rates. The results are summarized in figure 13 in terms of the additional available escape time beyond the baseline test without water discharge. The results of the SAVE test are also shown (108 seconds additional escape time). Each of the zoned tests indicated a significant improvement in the additional escape time, which was greater than the improvement with the SAVE system in 5 of the 9 cases.

The effectiveness of a water spray system per unit gallon of water discharged, or its efficiency, may be defined as the ratio of the additional available escape time to the quantity of water discharged. This efficiency is designated SPG, an abbreviation for its units, seconds per gallon. Figure 14 compares SPG for the various water spray configurations on the basis of nozzle flow rate. From figure 14 it is evident that the optimum nozzle type is the medium flow rate nozzle (0.35 gpm) and that the optimum zoned water spray configuration is a water quantity of 8 gallons. The optimum zoned water spray system (SPG = 20.4) is a factor of 13.6 more efficient than the SAVE water spray system (SPG = 1.5). It is significant that as much as 20 seconds of additional available escape time may be achieved by a water spray system, operating effectively in a postcrash fire environment, where each second of available escape time is critical.

5. SUMMARY

Full-scale fire tests demonstrated the effectiveness of an on-board water spray system, comprised of an array of ceiling nozzles, discharging water throughout an airplane cabin for 3 minutes. Approximately 2-3 minutes of additional survival time were provided for several postcrash fire scenarios in both narrow-body and wide-body test articles. Additional full-scale tests demonstrated that a zoned system, designed to discharge water at 300 °F in each zone, may provide even more protection with only about 10 percent of the weight of water.

6. REFERENCES

1. Sarkos, C.P., "Development of Improved Fire Safety Standards Adopted by the Federal Aviation Administration," AGARD-CPP-467, Propulsion and Energetics Panel 73rd Symposium on Aircraft Fire Safety, Sintra, Portugal, May 22-26, 1992.

2. Whitfield, R.T., Whitfield, Q.A., and Steel, J., "Aircraft Cabin Fire Suppression by Means of an Interior Water Spray System," Civil Aviation Authority, CAA Paper 88014, July 1988.

3. Hill, R.G., Sarkos, C.P., and Marker, T.R., "Development and Evaluation of an Onboard Aircraft Cabin Water Spray System for Postcrash Fire Protection," SAE Technical Paper 912224, Aerospace Technology Conference and Exposition, Long Beach, California, September 23-26, 1991.

4. Speitel, L.C., "Toxicity Assessment of Combustion Gases and Development of a Survival Model," Federal Aviation Administration, Report DOT/FAA/CT-91/26, to be published.

5. Marker, T.R., "On-Board Cabin Water Spray System Under Various Discharge Configurations," Federal Aviation Administration, Report DOT/FAA/CT-TN91/42, October 1991.

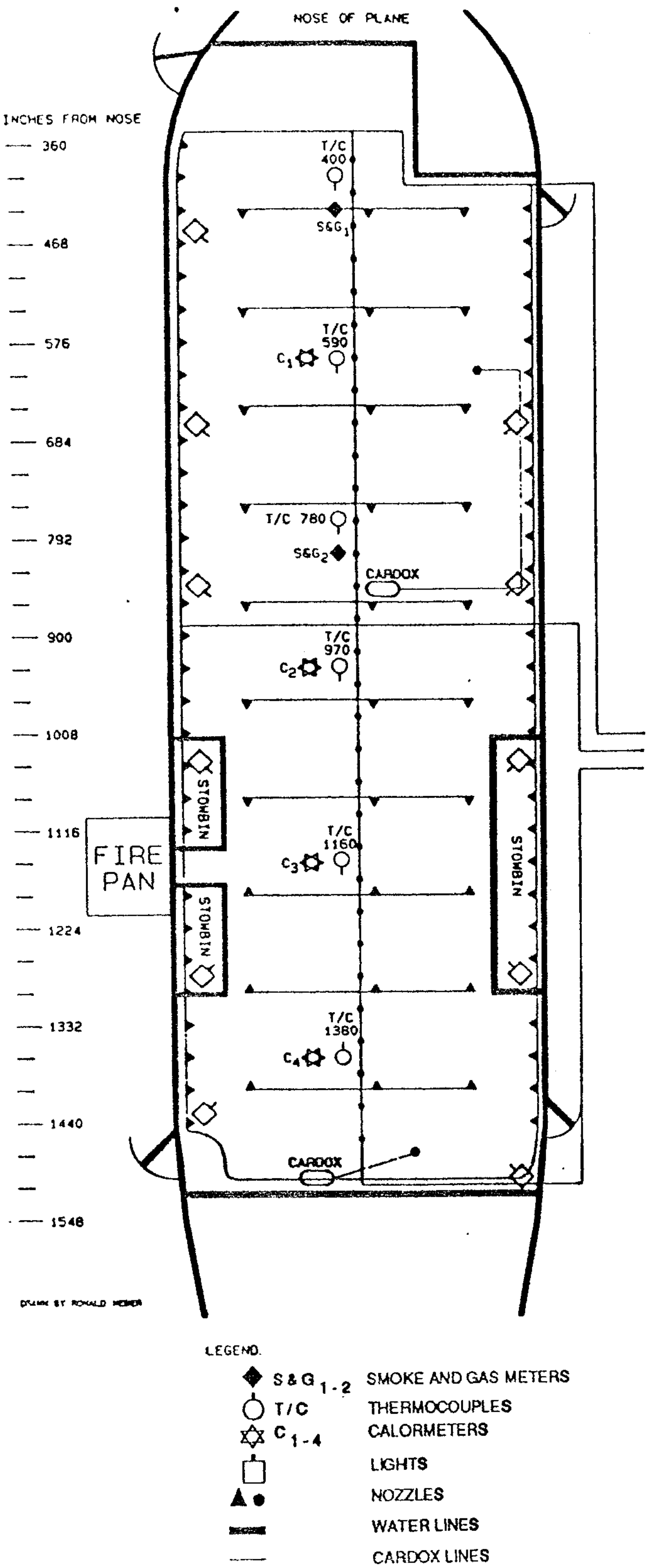

FIGURE 1.
NARROW BODY TESTCONFIGURATION

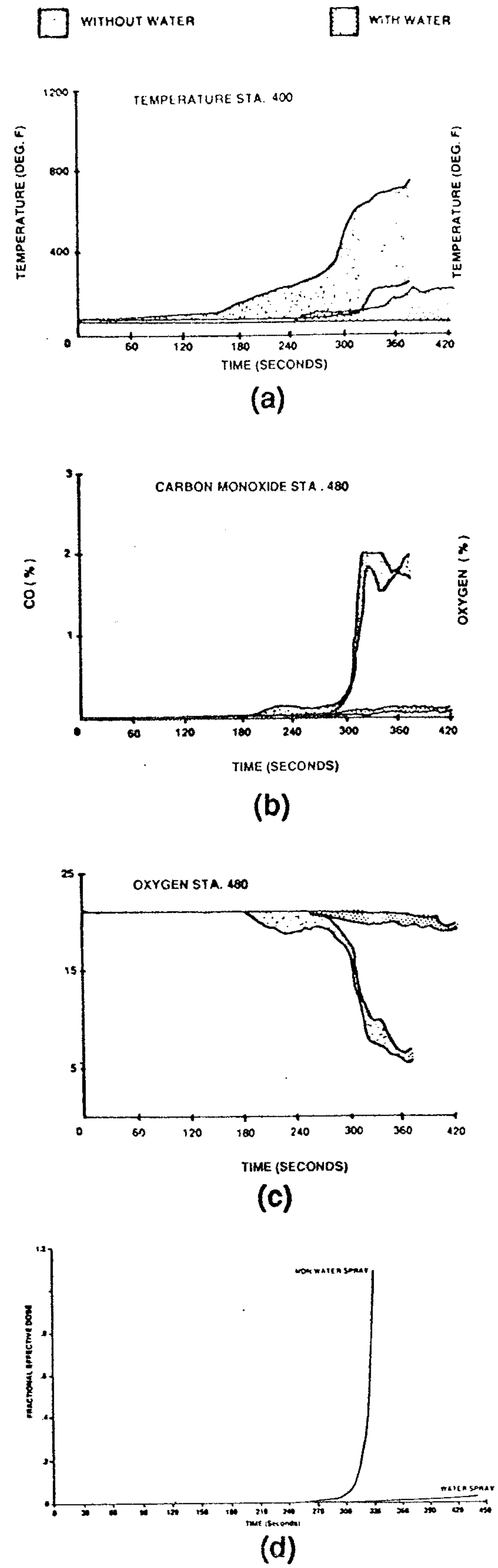

FIGURE 2.
NARROW BODY RESULTS/ SAVE SYSTEM/
ZERO WIND/ FUSELAGE OPENING

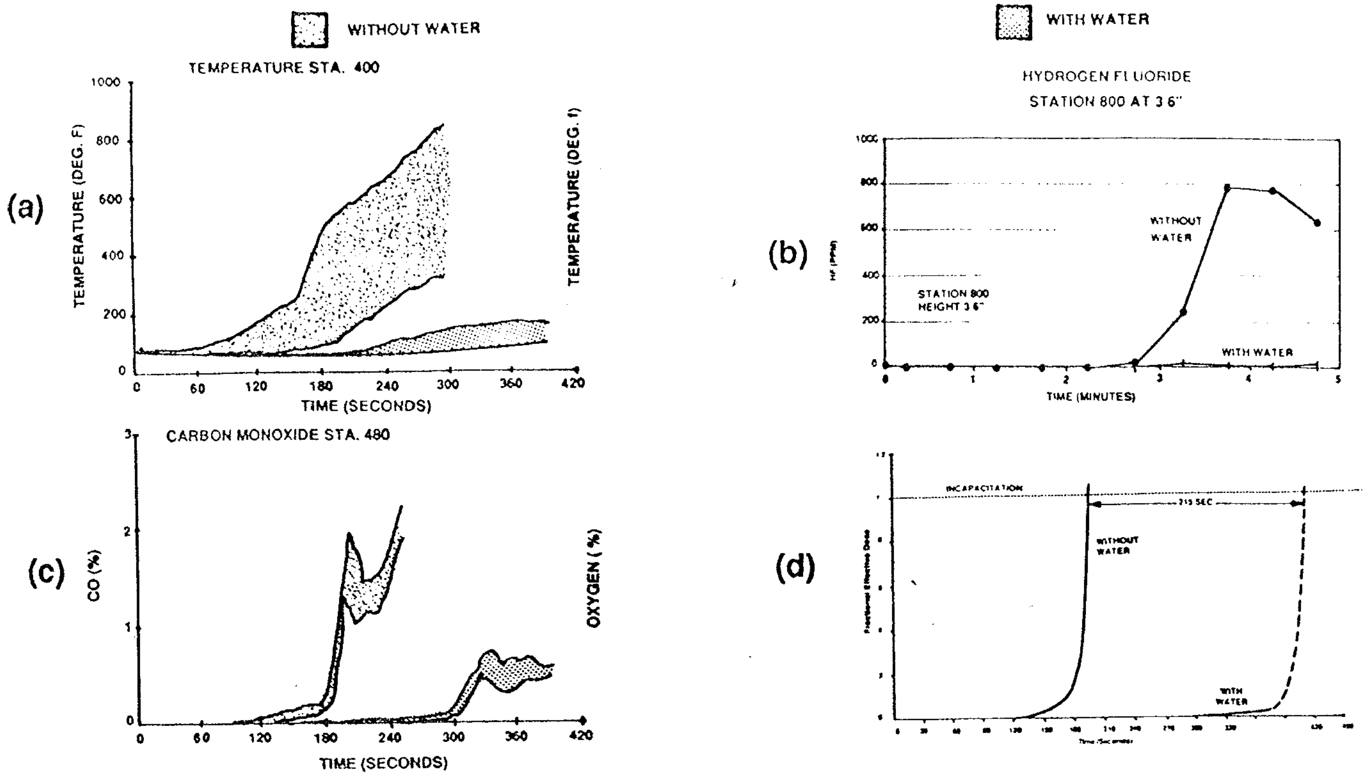

FIGURE 3.
NARROW BODY RESULTS/ SAVE SYSTEM/MODERATE WIND/FUSELAGE OPENING

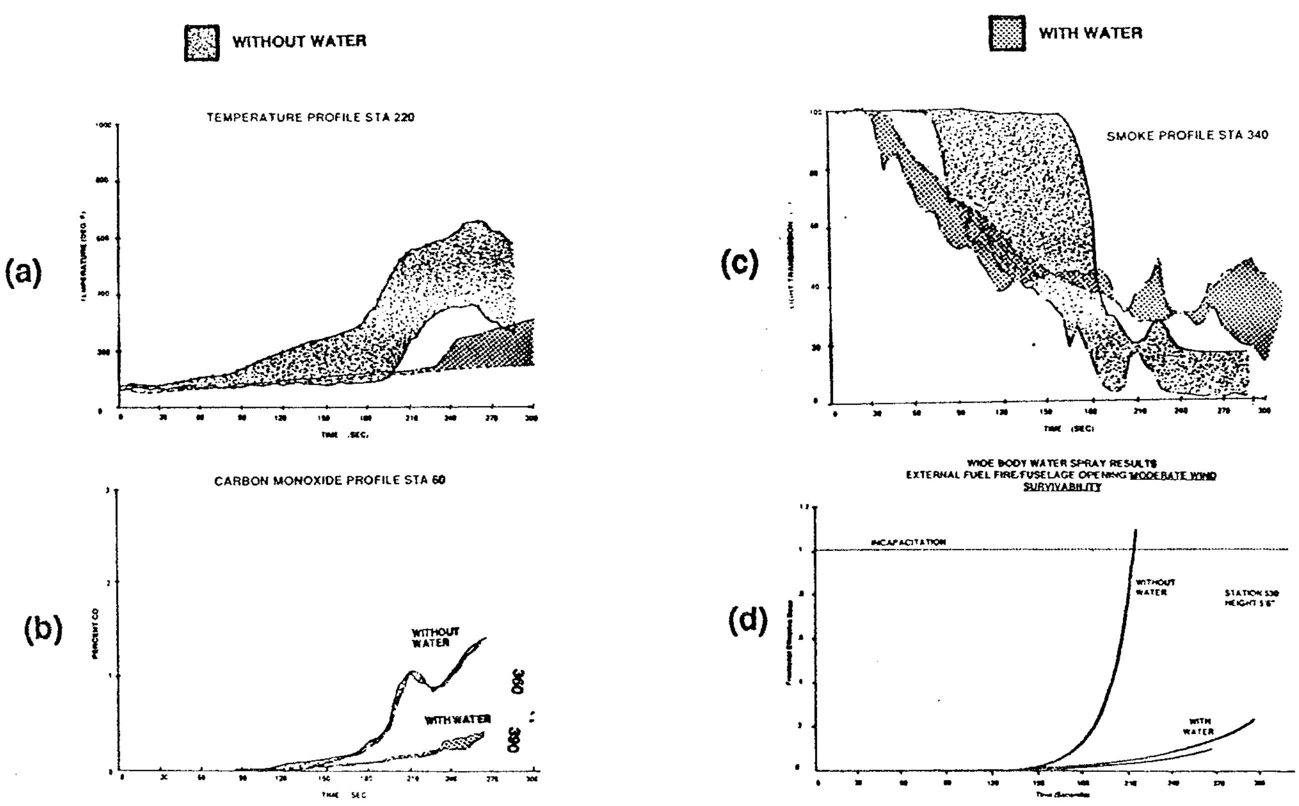

FIGURE 4.
WIDE BODY RESULTS/ SAVE SYSTEM/MODERATE WIND/FUSELAGE OPENING

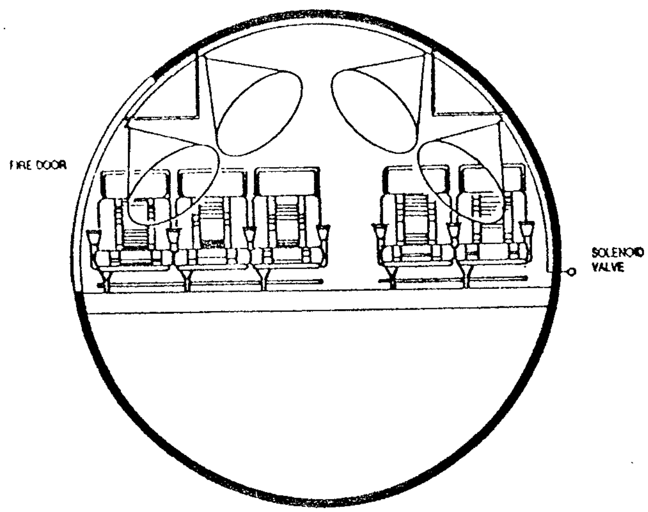

FIGURE 5.
ZONED SYSTEM DISCHARGE PATTERN

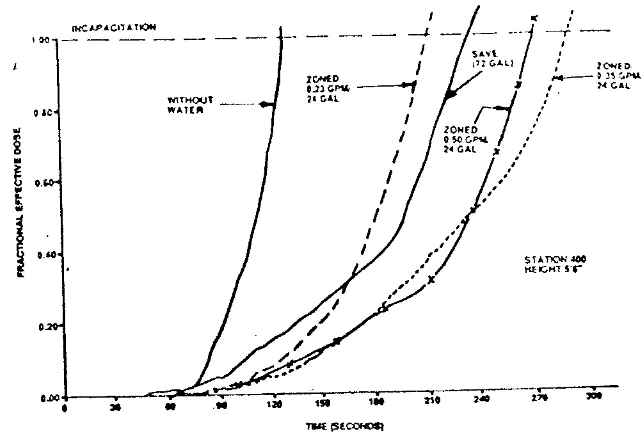

FIGURE 6.
ZONED SYSTEM SURVIVAL TIME
IMPROVEMENT 24 GALLONS

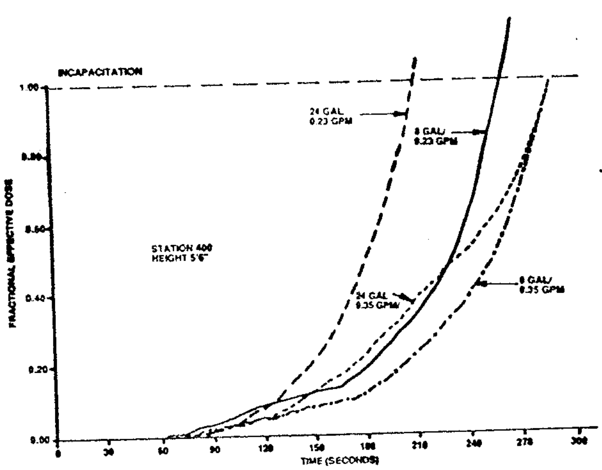

FIGURE 7.
ZONED SYSTEM SURVIVAL TIMES/24
AND 8 GALLONS

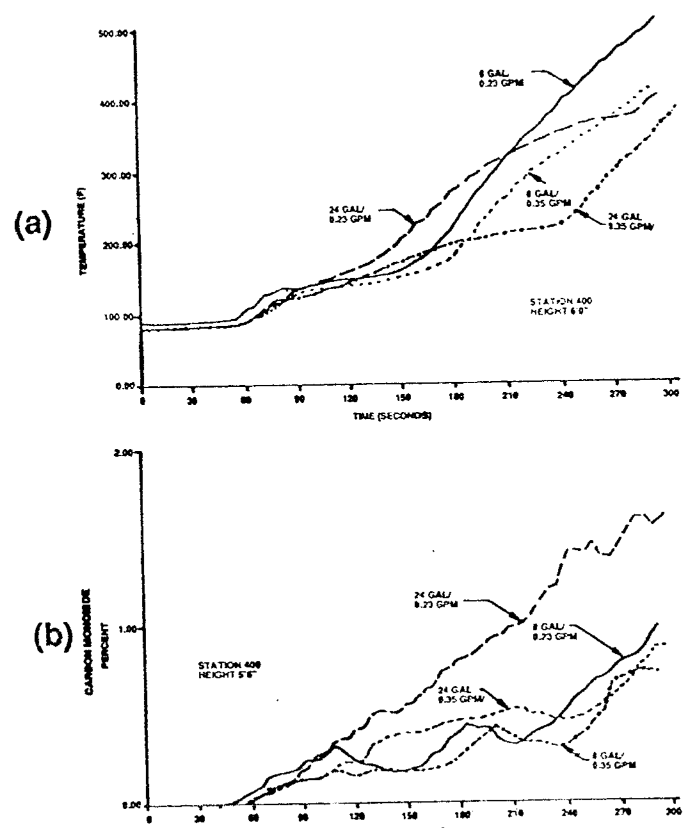

FIGURE 8.
ZONED SYSTEM/TEMPERATURE AND
CARBON MONOXIDE RESULTS/24
AND 8 GALLONS

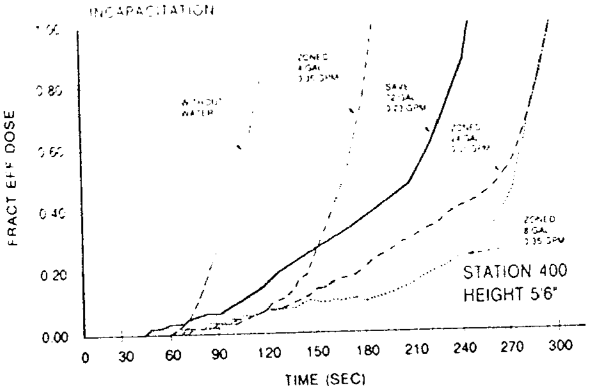

FIGURE 9
ZONED SYSTEM SURVIVAL TIME
IMPROVEMENT / 4, 8 AND 24 GALLONS

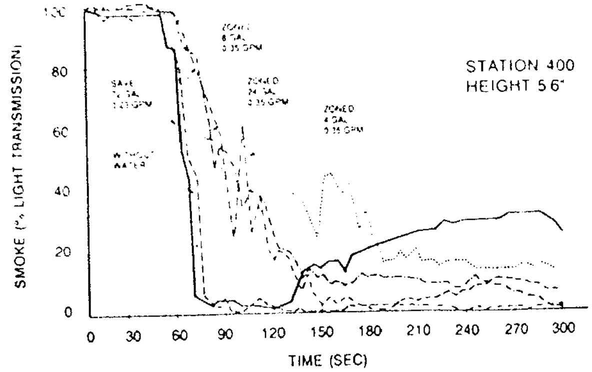

FIGURE 10
ZONED SYSTEM SMOKE OBSCURATION
IMPROVEMENT / HEIGHT = 5' 6"

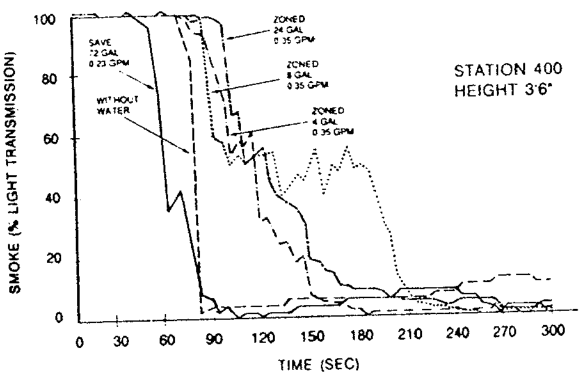

FIGURE 11
ZONED SYSTEM SMOKE OBSCURATION
IMPROVEMENT / HEIGHT = 3' 6"

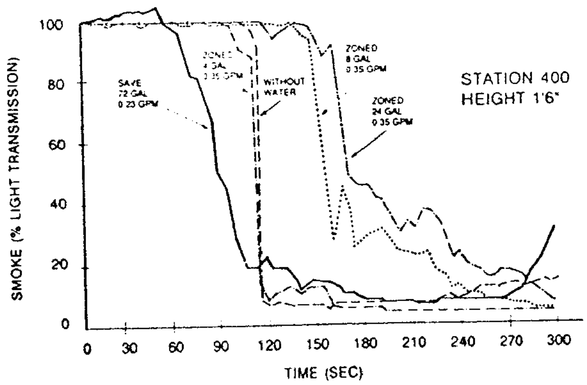

FIGURE 12
ZONED SYSTEM SMOKE OBSCURATION
IMPROVEMENT / HEIGHT = 1' 6"

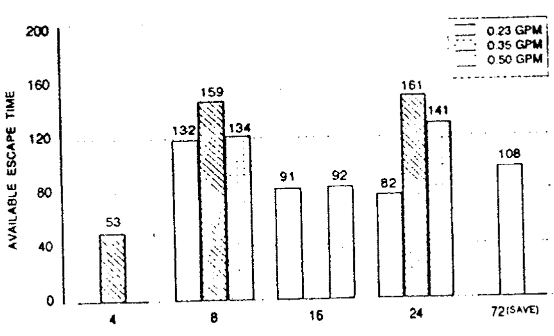

FIGURE 13
ZONED SYSTEM AVAILABLE
ESCAPE TIME

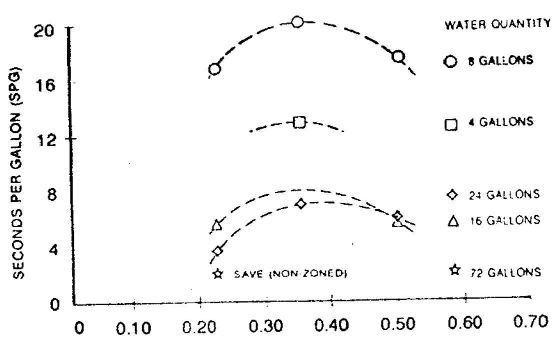

FIGURE 14
ZONED SYSTEM OPTIMIZATION

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Effectiveness of Seat Cushion Blocking Layer Materials against Cabin Fires

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Effectiveness of Seat Cushion Blocking Layer Materials against Cabin Fires

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ABSTRACT

Materials are available for preventing or retarding aircraft cabin fires involving urethane foam seat cushions. Realistic fire tests performed in a wide-body test article demonstrate that some in-flight and ramp fires can be prevented, and that the allowable time for safe evacuation can be significantly extended during a survivable postcrash fuel fire, when the urethane foam seat cushion is covered by a "blocking layer" material.

OBJECTIVE

The main objective of this paper is to describe the effectiveness of aircraft seat cushion blocking layer materials when subjected to various realistic cabin fire conditions.

BACKGROUND

The flammable nature of foamed plastics, in general, has focused attention on protecting or replacing urethane foam in such widespread residential applications as household insulation, upholstery furniture, and mattresses (reference 1). In transport aircraft, the large number of passenger seats constitute the major application for flexible urethane foam. Accordingly, the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee, convened by the Federal Aviation Administration (FAA) to "examine the factors effecting the ability of aircraft cabin occupants to survive in the postcrash environment and the range of solutions available," made the following recommendation: "Develop for aircraft seats, fire blocking layers (e.g., fire barriers) for polyurethane foam cushioning material, in order to retard fire spread" (reference 2). This paper describes FAA test results on candidate blocking layer materials evaluated in wide-body cabin test article under various realistic fire conditions. The effectiveness of the blocking layer material is judged by comparing seat test results, with and without blocking layer protection, under identical fire test conditions.

Aircraft cabin fires may be categorized as follows: ramp, in-flight, and postcrash. The characteristics of each are sufficiently distinct to require separate analysis. Ramp fires occur when an aircraft is parked at the ramp, usually in an unattended condition, but on less frequent occasions during servicing. Past ramp fire experience has resulted in loss of property but not loss of life. For example, a 727 was extensively damaged as a result of a fire originating from discarded smoking material placed inside a plastic disposal bag located adjacent to a passenger seat (reference 3). The loss was estimated at $3,200,000. The elapsed time before discovery of the fire, approximately 50 minutes, is consistent with the ability of polyurethane foam to support smoldering combustion for long periods of time, before transitioning to open flaming. Most in-flight fires occur in accessible areas, such as a galley, and are detected and extinguished promptly. On rare occasions in-flight fires become uncontrollable, leading to large loss of life. The most recent example was an L-1011 in-flight cargo compartment fire over Saudi Arabia, eventually claiming all 301 occupants onboard the airplane (reference 4). The fire became life threatening when flames penetrated through the cabin floor, involving seats and other interior materials. In the United States all fatalities attributable to fire

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occur in postcrash fire accidents (reference 5). Most postcrash cabin fires are accompanied by a large fuel spill fire. Burning interior materials may effect the survivability of cabin occupants in those accidents with a predominantly intact fuselage and a fuel fire adjacent to a fuselage opening, such as a rupture or door opening (references 6 and 7). Under these conditions, seats near a fuselage rupture or door opening will be subjected to intense thermal radiation and/or flames from the fuel fire.

DISCUSSION

BLOCKING LAYER MATERIALS - Over the past 20 years or more, the aircraft industry has constructed aircraft seat cushions from urethane foam, which possesses low weight and excellent comfort, resiliency and durability. In applications where weight is not a consideration, neoprene foam is a viable replacement for urethane foam when improved fire performance becomes a requirement (reference 8). However, neoprene foam is approximately 3 to 4 times as dense as urethane foam, and would create a prohibitive weight penalty in aircraft seating. A thin, lightweight blocking layer material, encapsulating the urethane foam to prevent or retard fire involvement of the urethane, is an attractive protective measure for aircraft seating. The blocking layer material is an interliner between the upholstery cover and foam cushion. In some cases it can also function as a ticking.

Table 1 is a list of candidate blocking layer materials for aircraft seating evaluated in this paper. There are two basic types of blocking layer materials; (1) foams, and (2) aluminized fabrics. The foam blocking layers are neoprene (polychloroprene), which is glued to the urethane foam. Upon exposure to heat or flame, neoprene foam blocking layers produce a relatively stable char, which acts as an insulator and reduces the rate of heat transfer to the urethane foam. Of the two foams listed, only Vonar® is marketed as a blocking layer; LS-200 is normally used as a full cushion. The lightest Vonar blocking layer has a cotton scrim and weighs 23.5 oz/yd^2.

A more recent blocking layer consideration is the aluminized fabrics, used primarily in protective clothing against heat or fire. These materials were identified by the National Aeronautics and Space Administration (NASA) as a possible alternate to a Vonar blocking layer at approximately 1/2 the weight (reference 9). Fabric blocking layers are designed to cover the urethane foam in the same manner as an upholstery cover, with the open end being sewn or fastened in some manner to completely cover the urethane. Fabric blocking layers are composed of high-temperature synthetic fibers, and an aluminized outer coating to reflect heat. The aluminized coating may also impart some degree of protection by preventing or delaying the the formation of urethane drippings on the floor which, if ignited, can contribute to the spread of fire (reference 10).

Table 1. Materials Tested

Material	Chemical Composition
Baseline	
(1) Wool (90%)/Nylon (10%) Fabric	-
(2) FR Urethane foam	-
Foam Blocking Layer	
(3) Vonar®, 3/16 in. thick	FR polychloroprene
(4) LS-200, 3/8 in. thick	FR polychloroprene
Fabric Blocking Layer	
(5) Norfab®, 13 oz/yd^2	Blend of predominatly aromatic polyamide fibers wrapped around a fiberglass fire core, aluminized outer surface.
(6) Preox®, 11 Oz/yd^2	Heat stabilized polyacrylonitrile, aluminized outer surface.

(1) Type of seat upholstery cover used in all tests
(2) Fire-retardant
(3) Registerd Trademark, DuPont Co., Wilmington, Delaware
(4) Product of Toyad Corporation, Latrobe, Pa.
(5) Registerd Trademark, Norfab Corporation, Norristown, Pa.
(6) Registerd Trademark, Gentex Corporation, Carbondale, Pa.

TEST ARTICLE

The test article was a C-133 aircraft, modified to resemble a wide-body cabin interior, as shown in figure 1 and in reference 11. The cross sectional area is similar to, although slightly smaller than, a wide-body cabin. An interior volume of 13,200 ft^3 is representative of a wide-body jet.

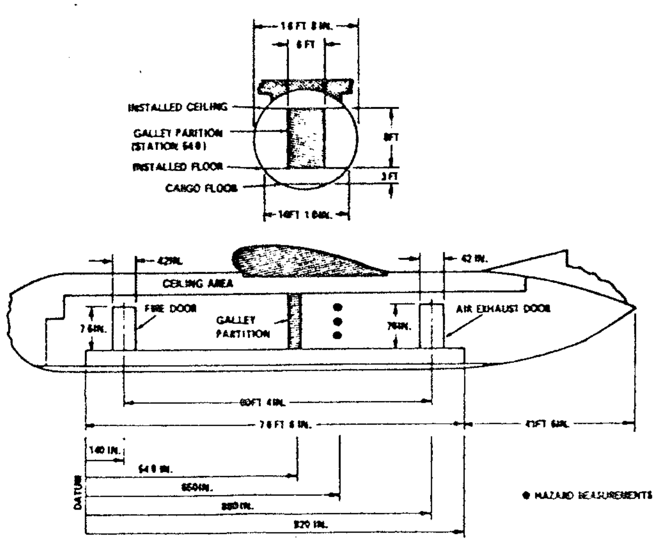


Figure 1. Schematic of C-133 Wide-Body Cabin Fire Test Article

All combustible materials installed in the original cargo aircraft were removed and the new floor, sidewall and ceiling surfaces are composed of noncombustible materials. A CO_2 total flooding system allows for the selective termination of a test. These protective measures have resulted in a durable test article, which has withstood hundreds of tests with only minor damage and thus allowed for the conduct of parametric studies with different materials or different fire test conditions.

The test article is extensively instrumented to measure the major hazards produced by a cabin fire as a function of time at various cabin locations. The following measurements are routinely taken: temperature, heat flux, smoke density, carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), acid gases (e.g., hydrogen fluoride (HF), hydrogen chloride (HCl)), and organic gases (e.g., hydrogen cyanide (HCN)). Video and photographic coverage documents the visual progress of the fire.

The C-133 test article was utilized to evaluate candidate blocking layer materials under test conditions representative of the three major types of cabin fires. Figure 2 illustrates the installation of interior materials in the forward part of the test article. The furnished test section is centered at the fuselage opening (test station 140) adjacent to an external fuel fire used in postcrash studies. For the postcrash test condition, an additional opening is provided at test station 880 (figure 1). A large fan behind the fire pan can be employed to simulate ambient wind and create penetration of fuel flames through the forward opening. Under both the ramp and in-flight test conditions, all fuselage openings are closed. For the in-flight condition, a ducting system was designed and installed in the test article to simulate ceiling air intake and baseboard air exhaust from a cabin environmental control system. One cabin air change occurs approximately every 3 minutes. No ventilation was used under the ramp fire condition.

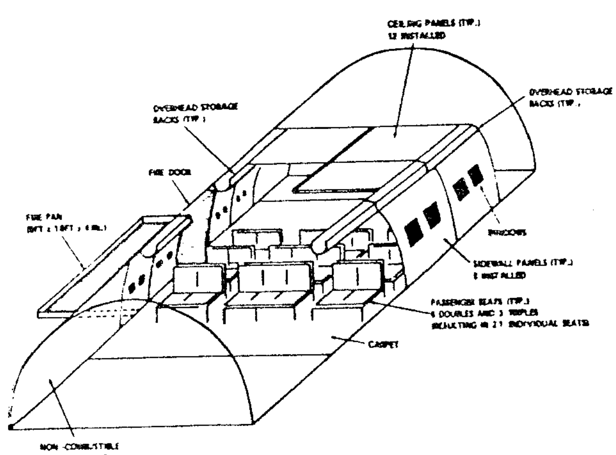


Figure 2. Installation of Wide-Body Materials Inside C-133 Test Article

During some of the tests only aircraft seats were subjected to the fire conditions (e.g., ramp and in-flight tests). This was necessary because of the great expense of the ceiling and sidewall panel materials and stowage bins. The seating configuration was always centered at test station 140.

IGNITION SOURCES

Table 2 lists the ignition sources used to evaluate the effectiveness of the candidate blocking layer materials. The plastic trash bag used in the ramp fire test was suggested by the 727 ramp fire discussed previously. Various ignition source intensities possible during an in-flight fire were employed, ranging from the relatively weak cigarette ignition to the more intense flight bag or gasoline fire. The burning flight bag ignition source, which was located underneath a seat, was also representative of floor burn through from a lower compartment. The most severe ignition source was the 80-square-foot fuel fire adjacent to a 76-inch by 42-inch fuselage opening, used to simulate a postcrash fire condition. Previous work had demonstrated that the intensity of the thermal radiation passing through an opening of this size was approximately 80 percent of the level produced by an infinitely large fuel fire under zero wind conditions (references 7 and 12).

Table 2. Test Ignition Sources

Type of Fire	Ignition Source
Ramp	• Plastic trash bag filled with approximately 18 ounces of paper towels and newspaper
In-Flight	• Cigarette • Newsprint (4 double sheets) • Gasoline (1 print) • Simulated nylon flight bag (contents 2 shirts and 2 double sheets of newsprint approximately 22 ounces)
Postcrash	• Jet fuel (80-square-foot pan containing 50 gallons of fuel)

TEST RESULTS

RAMP FIRE - In the ramp fire tests, three rows of triple aircraft seats, with each row containing two sets of triple seats and a section of carpet under the center row, were installed in the test article. The trash bag was placed adjacent to an outer seat in the middle row and ignited with a match. Figure 3 compares results for a test with unprotected cushions and a test with cushions protected with an LS-200 blocking layer. The results demonstrated that the use of a foam blocking material on seat cushions can prevent a ramp fire which would become out of control in 3 to 5 minutes, if the seats were not protected.

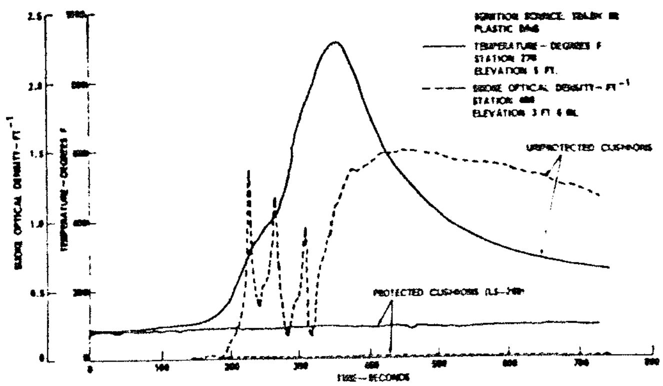


Figure 3. Seat Cushion Blocking Layer Benefit—Ramp Fire Scenario

Figure 3 indicates that the target seat became significantly involved in fire in about 3 to 3 1/2 minutes. By almost 6 minutes oxygen depletion caused the flames to subside and the fire to transition to a smouldering stage, evidenced by the temperature peak and subsequent decrease in temperature and by the persistent increase in smoke level. Although not shown in the figure, the seats reignited into a flaming mode when a door to the test article was opened, because the supply of oxygen in the cabin was replenished. Eventually, all 6 sets of triple seats were consumed by fire.

IN-FLIGHT FIRE (C-133) - The in-flight fire test setup was identical to that used in the ramp fire tests with two exceptions: (1) simulated cabin air ventilation was employed, and (2) the ignition source was placed under (versus adjacent to) the target seat (same seat location). Figure 4 compares the temperature history slightly

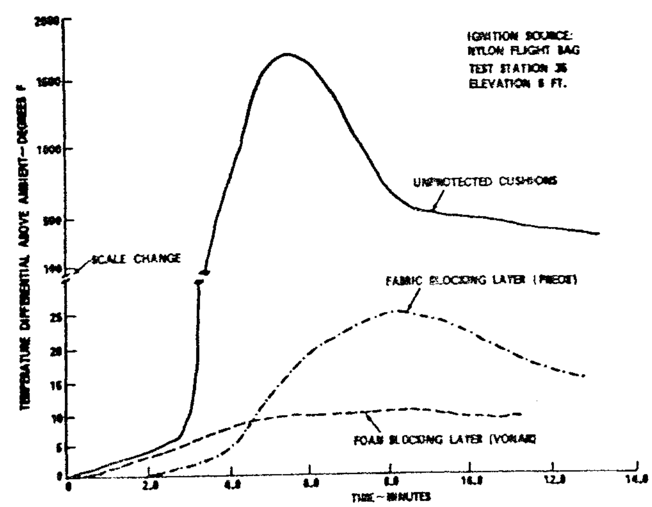


Figure 4. Seat Cushion Blocking Layer Benefit—In-Flight Scenario

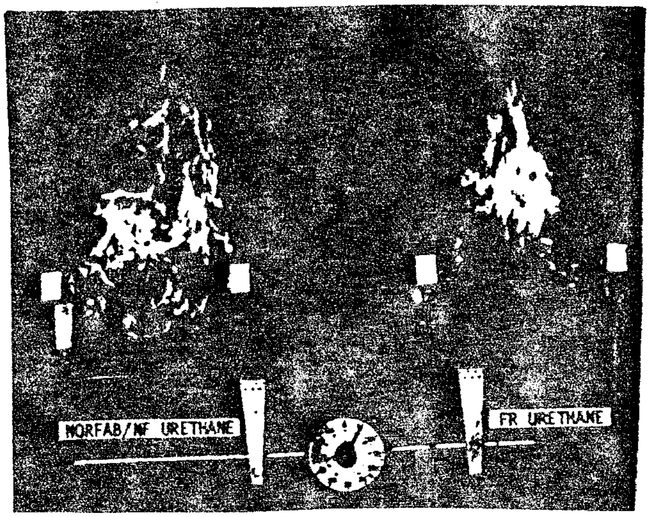
forward of the fire origin in tests with foam blocking layer protection, fabric blocking layer protection and no seat protection. Both types of blocking layer materials prevented a fire which would have spread uncontrolably without seat protection. Based on the peak temperatures, the foam blocking layer was more effective than the fabric blocking layer, although both types of material prevented fire spread beyond the vicinity of the ignition source.

The ramp and in-flight test results were similar in terms of the time interval from ignition to a significant increase in cabin temperature — approximately 3 minutes in both cases. This finding was probably due to the weights of the ignition sources being nearly equivalent. However, the in-flight ignition source was observed to continue burning for a longer time than the ramp fire ignition source. From figure 4, it appears that the in-flight source fire persisted for 8 minutes, apparently because of the slower-burning clothing materials.

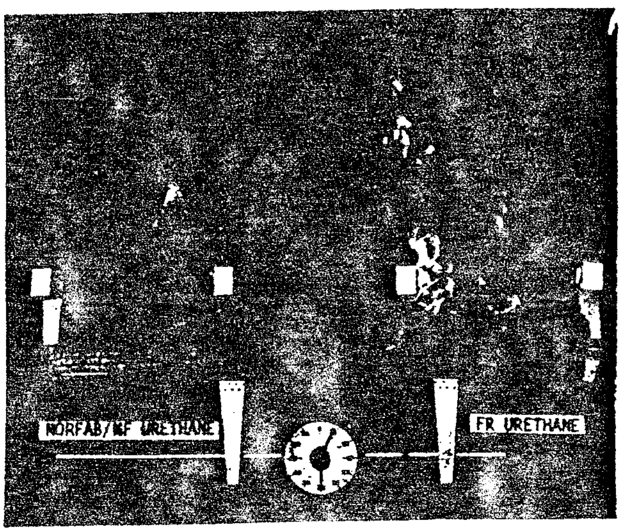
From a practical viewpoint, the time interval before significant seat involvement, without blocking layer protection, under most circumstances would be adequate for cabin crewmembers to extinguish the fire with hand-held extinguishers. Fires of this nature can be extinguished in 5 to 10 seconds under optimum fire-fighting conditions (e.g., immediate agent application, unobstructed access to base of fire, etc.). However, extenuating circumstances such as panic, or perhaps the fire origin being beneath the cabin floor, suggest the potential benefits of additional protection.

EFFECT OF FLAME RETARDANT IN URETHANE - In this period of unpredictable fuel costs, airplane operators continually strive for weight reduction. When a blocking layer material is employed, an increase in seat weight will be incurred. One method of minimizing the potential weight penalty of fire blocking layers is to utilize a nonfire-retardant (NF) urethane foam cushion, which is about 20 percent lighter than fire-retardant (FR) urethane foam. A series of tests were performed to determine if the use of a blocking layer over NF urethane foam presented any greater in-flight fire hazard than presently used FR urethane foam. Tests were also performed to study and compare the behavior of FR cushions with various blocking layers.

The tests were conducted in an open test bay area using a single aircraft triple seat (reference 13). The middle seat cushions were removed and the outer seats were configured in accordance to the comparison under study; e.g., in one test, both seats were protected with a foam blocking layer, but an NF foam was used in one seat and an FR foam in the other. For a given test, each seat was subjected to an identical ignition source. Figure 5 shows test results with newspaper ignition on the seat, with one seat comprised of an NF urethane foam protected with a fabric blocking layer and the other seat comprised of unprotected FR urethane foam. At 90 seconds, the protected seat had self-extinguished, while the unprotected seat fire was essentially out of control.



(t = 15 seconds)



(t = 90 seconds)

Figure 5. Seat Performance Against Newspaper Fire

Table 3 is a generalization of the in-flight ignition source results. It is apparent that either foam or fabric blocking layers over NF urethane cushions can prevent in-flight fires, which if left uncontrolled, can spread beyond the ignition source when the cushion is simply FR urethane. Moreover, when a blocking layer material is utilized, the presence or not of fire retardants in the urethane foam cushion will not have a bearing on the ultimate result, which is self-extinguishment of the seat fire. During replicate tests with blocking layer materials, the time to self-extinguishment depended on whether other seat components (e.g., armrest, tray back) were ignited. If these components were not involved, the fire was essentially out after the ignition source was consumed. When the seat components became involved, the fire burned, appreciably longer before self-extinguishing. During this latter kind of behavior, the fire intensity and growth was subdued compared to the burning of an unprotected seat. Thus, blocking layer materials were effective even when seat components other than the cushions were ignited.

Table 3. Generalization of Small Ignition Source Results

	Blocking Layer Type				
	None	Foam		Fabric	
	Urethane Foam Treatment				
Ignition Source	FR	FR	NF	FR	NF
Cigarette	Self-Extinguished	Self-Extinguished	Self-Extinguished	Self-Extinguished	Self-Extinguished
Newspapers on Seat	Destroyed Seat	Self-Extinguished	Self-Extinguished	Self-Extinguished	Self-Extinguished
Newspapers under Seat	Destroyed Seat	Self-Extinguished	Self-Extinguished	Self-Extinguished	Self-Extinguished
Gasoline (1 pint)	Destroyed Seat	Self-Extinguished	Self-Extinguished	Self-Extinguished	Self-Extinguished

FR Fire-Retardant
NF Nonfire-Retardant

POSTCRASH FIRE (FULL-SCALE TESTS) - The postcrash fire tests were the most realistic undertaken. In these tests, a section of the C-133 test article was realistically lined and furnished with surplus or new wide-body materials, as illustrated in figure 2 and reference 7. The main objective was to examine the postcrash fire benefit of seat cushion blocking layer materials within the context of the remaining interior materials. The materials were subjected to a zero wind fuel fire adjacent to a large (22 ft^2) fuselage opening. Prior testing had demonstrated that a zero wind condition would produce minimal cabin hazards from the fuel fire; therefore, any hazards detected with interior materials installed could be attributed to the burning materials. Four full-scale tests were conducted with the only variable being the cushion makeup. The following cushions were tested: (1) unprotected (FR urethane) cushion, (2) FR urethane cushion with foam (Vonar) blocking layer, (3) FR urethane cushion with fabric (Norfab®) blocking layer, and (4) noncombustible (ceramic fiber glass) cushion.

In each of the tests, the fuel fire ignited the interior and produced a condition called "flashover," which occurred at a different point in time in each test. Flashover corresponds to a rapid growth of the fire from an area in the immediate vicinity of the fuel fire to the remaining cabin interior.

In order to quantitate the hypothetical survival time, a simple human survival model was developed which considers the effects of elevated temperature, CO_2, CO, HCN, HF, and HCl (reference 7). The major assumptions were that the hazards are additive and that a classical hyperbolic relationship exists between gas concentration and time of incapacitation. The model is hypothetical, and was developed as a tool for reducing a number of somewhat abstract hazard measurements into a single, cogent parameter-survival time.

The model was applied to analyze the survivability associated with the four full-scale fire tests with different cushion makeups. In the model, a variable called the mixture fractional effective dose (FED) is defined. It is calculated at each time increment analyzed, and is essentially the sum of the ratios for each hazard of measured dose to the incapacitation dose. Thus, the hypothetical survival time corresponds to that point in time when FED = 1.0.

Figure 8 is a plot of the calculated FED versus time in the aft cabin for the four full-scale fire tests. This plot indicates the safety benefit, in terms of increase in survival time, associated with seat blocking layer materials under the postcrash fire condition tested. The calculated FED does not include the effect of HCl in any of the tests because a malfunction in the analysis of HCl in one of the tests. The safety benefit of Vonar and Norfab blocking layer materials — 60 and 43 seconds, respectively — is considered significant, especially since the benefit is incurred within the context of the remaining interior materials. In addition, the results indicate that the amount of protection provided by Vonar is nearly equivalent to that of a noncombustible cushion, under the fire conditions studied. (Note that the improvement in survival time with the noncombustible cushions was only 8 seconds better than with the Vonar protected cushions.) The shape of the FED profiles indicate to some degree the rapidity by which conditions become nonsurvivable after the onset of flashover. In fact, the calculated safety benefit (survival time increase) for each of the protected cushion tests corresponds to the increase in time before the onset of flashover relative to the unprotected cushion test. Figure 8 also indicates that FED = 0 throughout the time framework of interest when the interior is noncombustible. This finding indicates that potential safety benefits exist, beyond that provided by seat blocking layers, by making improvements in the fire performance of other important interior materials; e.g., ceiling panels and overhead stowage bins.

Smoke was not a component of the human survival model. However, the impact of visibility obscuration resulting from smoke was calculated (reference 7). Figure 9 is a plot of cabin visibility in the aft cabin versus time for the four full-scale material tests. The most striking feature of the curves is the rapidity by which visibility becomes obscured, e.g., in some cases visibility was reduced from the length of the cabin to less than the width of the cabin in approximately 15 seconds. Also, by comparing figures 8 and 9, it is apparent that smoke becomes an important factor anywhere from 30 to 60 seconds before survival is no longer theoretically possible. This comparison also reveals that the ranking of results from best to worst for visibility loss was identical to the rankings for loss in survival time (i.e., noncombustible cushions > Vonar > Norfab > unprotected cushions).

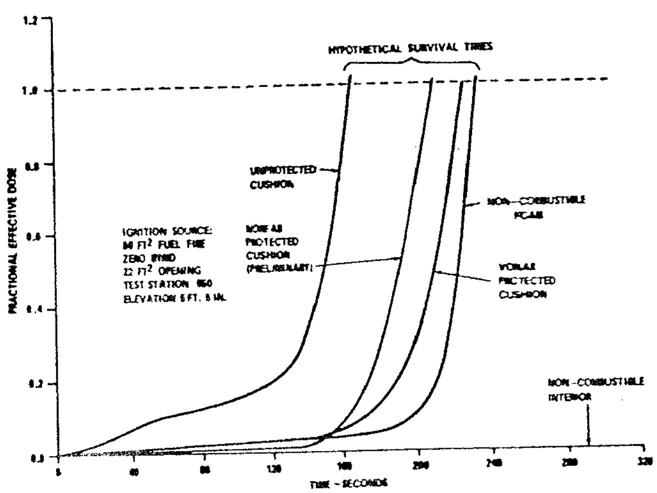


Figure 8. Effect of Cushioning Protection on Calculated Survival time Under Full-Scale Postcrash Fire Conditions

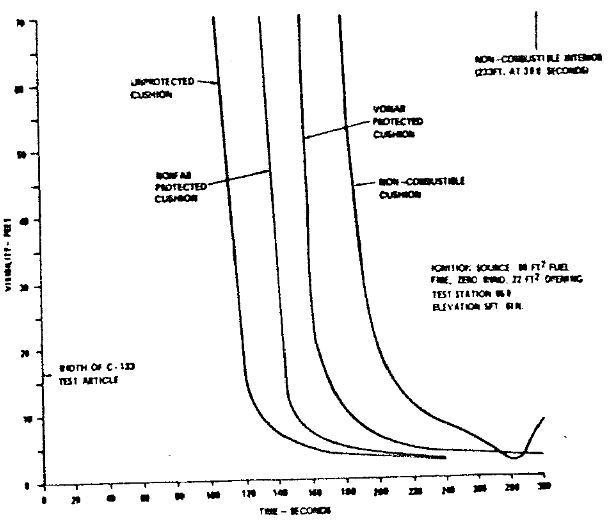


Figure 9. Effect of Cushioning Protection on Calculated Visibility Through Smoke Under Full-Scale Postcrash Fire Conditions

POSTCRASH FIRE (OTHER SCENARIOS) - The postcrash fire scenario discussed above was conceived for the purpose of creating a realistic impact-survivable fire situation wherein burning cabin materials have a dominant, if not controlling, effect on survivability. Obviously, a large number of other, and, perhaps more likely survivable postcrash fire conditions are possible. Another condition studied was a 2-foot-square opening, simulating a small fuselage rupture above the cabin floor, adjacent to the large external fuel fire. Because of the small rupture area, a simulated 3 miles per hour (mph) wind was utilized to intensify the cabin exposure conditions. Four double seats — three outboard and one inboard — symmetrically placed about the small rupture, were tested under these conditions. No other materials were placed in the test article. Figure 10 displays the cabin temperature history for three types of seating materials and for the fuel fire without seats. The results exhibit data crossover and small discrimination in the performance of different materials. For these reasons, this scenario was not utilized except for the above tests. The data also demonstrates that wind conditions created significant fuel-fire hazards inside the cabin. Under the conditions tested, approximately 50 percent of the cabin hazards were caused by the fuel fire.

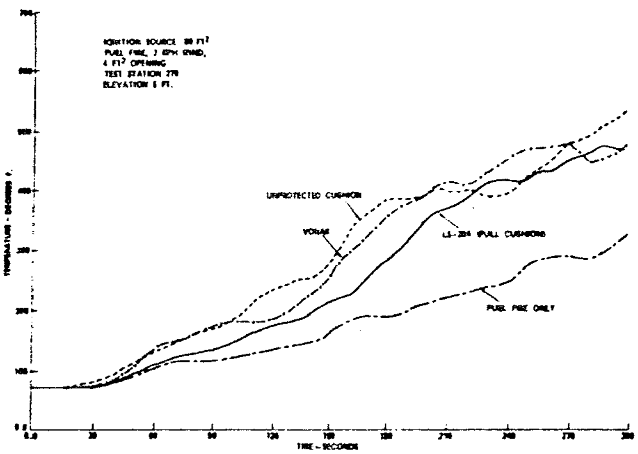


Figure 10. Postcrash Fire Test Results With Small Fuselage Opening and Wind

Another possible postcrash fire scenario consists of an intact fuselage with a door opening adjacent to a large external fuel fire. This scenario was also studied briefly, and is very similar to a past accident (reference 14). In these tests, a single triple outboard seat was located fore and aft of the type A door opening, and a 1.5 mph simulated wind was employed to create slight flame penetration into the cabin. Figure 11 compares temperature and smoke histories in tests with Vonar protected cushions and with unprotected cushions. In the test with protected cushions, the seat fire damage was minor and confined to the seat upholstery cover and various seat components; the flammable urethane foam did not become involved. By contrast, in the test with unprotected cushions, the fire became out of control in 3 to 4 minutes.

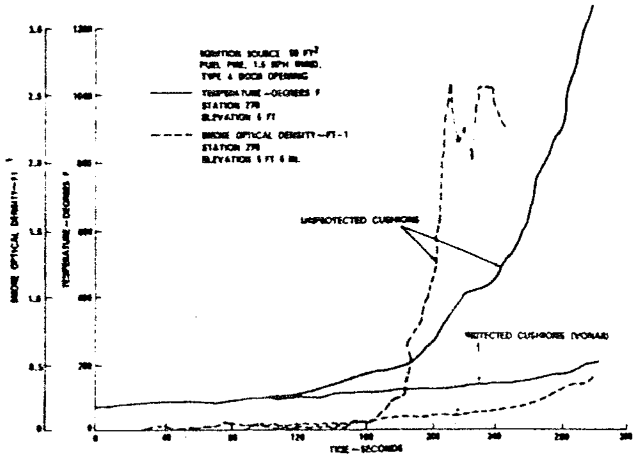


Figure 11. Seat Cushion Blocking Layer Benefit—Postcrash Fuel Fire Adjacent to Open Door

Thus, under this fire scenario, the benefit of seat cushion blocking layers is significant. An analysis of the results acquired for the three postcrash fire scenarios, as presented in figures 8, 10, and 11, demonstrate that potential benefits of seat cushion fire blocking layer materials are highly dependent upon fire scenario.

SUMMARY OF SIGNIFICANT FINDINGS

Based on the realistic cabin fire tests and analysis described in this paper, and on the seat cushion blocking layer materials evaluated and the types of fire test conditions employed, the following are the significant findings:

(1) Seat cushion fire blocking layer materials such as neoprene foam or aluminized high-temperature fabrics can prevent ramp and in-flight fires which become out of control when initiated at an unprotected seat and left unattended.

(2) Seat cushion fire blocking layer materials can significantly increase the safe time available for evacuation during specific types of postcrash cabin fire scenarios.

(3) Under severe fire conditions, such as a postcrash fuel fire, neoprene foam materials are more effective seat cushion blocking layers than aluminized high-temperature fabrics.

(4) Fire-retardant urethane foam can be replaced by nonfire-retardant urethane foam in aircraft seat cushions covered with a blocking layer material without essentially any loss in in-flight fire protection.

REFERENCES

1. "Fire Research on Cellular Plastics: The Final Report of the Products Research Committee," Library of Congress Catalog Card Number: 80-83306, April 1980.

2. "Final Report on the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee," Federal Aviation Administration, Volume I, Report FAA-ASF-80-4, June 26, 1980.

3. "Bi-Monthly Fire Record," Fire Journal, Vol. 74, No. 2, p. 22, March 1980.

4. "Aircraft Accident Report: Saudi Arabian Airlines, Lockheed L-1011, HZ-AHK, Riyadh, Saudi Arabia, August 19, 1980," Presidency of Civil Aviation, Jeddah, Saudi Arabia, January 16, 1982.

5. "Special Study: U.S. Air Carrier Accidents Involving Fire, 1965 through 1974, and Factors Affecting the Statistics," National Transportation Safety Board, Report NTSB-AAS-77-1, February 17, 1977.

6. Eklund, T.I. and Sarkos, C.P., "The Thermal Impact of External Fuel Fires on Aircraft Fuselages, Journal of Fire and Flammability, Vol. II, pp. 231-240, July 1980.

7. Sarkos, C.P., Hill, R.G., and Howell, W.D., "The Development and Application of a Full-Scale Wide Body Test Article to Study the Behavior of Interior Materials During a Postcrash Fuel Fire," AGARD Lecture Series No. 123 on Aircraft Fire Safety, AGARD-LS-123, June 1982.

8. Morford, R.H., "The Flammability of Neoprene Cushioning Foam," Journal of Fire and Flammability, Vol. 8, pp 279 - 299, July 1977.

9. Kourtides, D.A. and Parker, J.A., "Test Methodology for Evaluation of Fireworthy Aircraft Seat Cushions," Journal of Fire and Flammability, Vol. 15, pp. 56 - 76, January 1982.

10. Schutter, K.J. and Duskin, F.E., "Study for the Optimization of Aircraft Seat Cushion Fire Blocking Layers - Full Scale - Test Description and Results," NASA Contractor Report, Contract NASA2-11905, Douglas Aircraft Company, Report No. MDC J2525, May 1982.

11. Hill, R.G., Johnson, G.R., and Sarkos, C.P., "Postcrash Fuel Fire Hazard Measurements in a Wide-Body Aircraft Cabin," Federal Aviation Administration, NAFEC, Report FAA-NA-79-42, December 1979.

12. Eklund, T.I., "Pool Fire Radiation through a Door in a Simulated Aircraft Fuselage," Federal Aviation Administration, NAFEC, Report FAA-RD-78-135, December 1978.

13. Hill, R.G., et al, "Aircraft Seat Fire Blocking Layers; Effectiveness and Benefits Under Various Fire Scenarios," Federal Aviation Administration, report to be published.

14. "Aircraft Accident Report: Continental Air Lines, Inc., McDonnell-Douglas DC-10-10, N68045, Los Angeles, California, March 1, 1978," National Transportation Safety Board, Report NTSB-AAR-79-1, January 25, 1979.

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ABSTRACT

Materials are available for preventing or retarding aircraft cabin fires involving urethane foam seat cushions. Realistic fire tests performed in a wide-body test article demonstrate that some in-flight and ramp fires can be prevented, and that the allowable time for safe evacuation can be significantly extended during a survivable postcrash fuel fire, when the urethane foam seat cushion is covered by a "blocking layer" material.

OBJECTIVE

The main objective of this paper is to describe the effectiveness of aircraft seat cushion blocking layer materials when subjected to various realistic cabin fire conditions.

BACKGROUND

The flammable nature of foamed plastics, in general, has focused attention on protecting or replacing urethane foam in such widespread residential applications as household insulation, upholstery furniture, and mattresses (reference 1). In transport aircraft, the large number of passenger seats constitute the major application for flexible urethane foam. Accordingly, the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee, convened by the Federal Aviation Administration (FAA) to "examine the factors effecting the ability of aircraft cabin occupants to survive in the postcrash environment and the range of solutions available," made the following recommendation: "Develop for aircraft seats, fire blocking layers (e.g., fire barriers) for polyurethane foam cushioning material, in order to retard fire spread" (reference 2). This paper describes FAA test results on candidate blocking layer materials evaluated in wide-body cabin test article under various realistic fire conditions. The effectiveness of the blocking layer material is judged by comparing seat test results, with and without blocking layer protection, under identical fire test conditions.

Aircraft cabin fires may be categorized as follows: ramp, in-flight, and postcrash. The characteristics of each are sufficiently distinct to require separate analysis. Ramp fires occur when an aircraft is parked at the ramp, usually in an unattended condition, but on less frequent occasions during servicing. Past ramp fire experience has resulted in loss of property but not loss of life. For example, a 727 was extensively damaged as a result of a fire originating from discarded smoking material placed inside a plastic disposal bag located adjacent to a passenger seat (reference 3). The loss was estimated at $3,200,000. The elapsed time before discovery of the fire, approximately 50 minutes, is consistent with the ability of polyurethane foam to support smoldering combustion for long periods of time, before transitioning to open flaming. Most in-flight fires occur in accessible areas, such as a galley, and are detected and extinguished promptly. On rare occasions in-flight fires become uncontrollable, leading to large loss of life. The most recent example was an L-1011 in-flight cargo compartment fire over Saudi Arabia, eventually claiming all 301 occupants onboard the airplane (reference 4). The fire became life threatening when flames penetrated through the cabin floor, involving seats and other interior materials. In the United States all fatalities attributable to fire

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occur in postcrash fire accidents (reference 5). Most postcrash cabin fires are accompanied by a large fuel spill fire. Burning interior materials may effect the survivability of cabin occupants in those accidents with a predominantly intact fuselage and a fuel fire adjacent to a fuselage opening, such as a rupture or door opening (references 6 and 7). Under these conditions, seats near a fuselage rupture or door opening will be subjected to intense thermal radiation and/or flames from the fuel fire.

DISCUSSION

BLOCKING LAYER MATERIALS - Over the past 20 years or more, the aircraft industry has constructed aircraft seat cushions from urethane foam, which possesses low weight and excellent comfort, resiliency and durability. In applications where weight is not a consideration, neoprene foam is a viable replacement for urethane foam when improved fire performance becomes a requirement (reference 8). However, neoprene foam is approximately 3 to 4 times as dense as urethane foam, and would create a prohibitive weight penalty in aircraft seating. A thin, lightweight blocking layer material, encapsulating the urethane foam to prevent or retard fire involvement of the urethane, is an attractive protective measure for aircraft seating. The blocking layer material is an interliner between the upholstery cover and foam cushion. In some cases it can also function as a ticking.

Table 1 is a list of candidate blocking layer materials for aircraft seating evaluated in this paper. There are two basic types of blocking layer materials; (1) foams, and (2) aluminized fabrics. The foam blocking layers are neoprene (polychloroprene), which is glued to the urethane foam. Upon exposure to heat or flame, neoprene foam blocking layers produce a relatively stable char, which acts as an insulator and reduces the rate of heat transfer to the urethane foam. Of the two foams listed, only Vonar® is marketed as a blocking layer; LS-200 is normally used as a full cushion. The lightest Vonar blocking layer has a cotton scrim and weighs 23.5 oz/yd^2.

A more recent blocking layer consideration is the aluminized fabrics, used primarily in protective clothing against heat or fire. These materials were identified by the National Aeronautics and Space Administration (NASA) as a possible alternate to a Vonar blocking layer at approximately 1/2 the weight (reference 9). Fabric blocking layers are designed to cover the urethane foam in the same manner as an upholstery cover, with the open end being sewn or fastened in some manner to completely cover the urethane. Fabric blocking layers are composed of high-temperature synthetic fibers, and an aluminized outer coating to reflect heat. The aluminized coating may also impart some degree of protection by preventing or delaying the the formation of urethane drippings on the floor which, if ignited, can contribute to the spread of fire (reference 10).

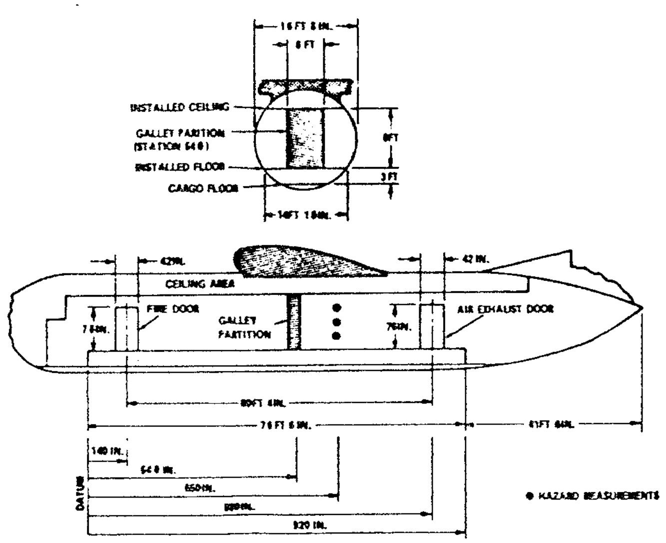
Table 1. Materials Tested

Material	Chemical Composition
Baseline	
(1) Wool (90%)/Nylon (10%) Fabric	-
(2) FR Urethane foam	-
Foam Blocking Layer	
(3) Vonar®, 3/16 in. thick	FR polychloroprene
(4) LS-200, 3/8 in. thick	FR polychloroprene
Fabric Blocking Layer	
(5) Norfab®, 13 oz/yd^2	Blend of predominantly aromatic polyamide fibers wrapped around a fiberglass fire core, aluminized outer surface.
(6) Preox®, 11 Oz/yd^2	Heat stabilized polyacrylonitrile, aluminized outer surface.

(1) Type of seat upholstery cover used in all tests
(2) Fire-retardant
(3) Registered Trademark, DuPont Co., Wilmington, Delaware
(4) Product of Toyad Corporation, Latrobe, Pa.
(5) Registered Trademark, Norfab Corporation, Norristown, Pa.
(6) Registered Trademark, Gentex Corporation, Carbondale, Pa.

TEST ARTICLE

The test article was a C-133 aircraft, modified to resemble a wide-body cabin interior, as shown in figure 1 and in reference 11. The cross sectional area is similar to, although slightly smaller than, a wide-body cabin. An interior volume of 13,200 ft^3 is representative of a wide-body jet.



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All combustible materials installed in the original cargo aircraft were removed and the new floor, sidewall and ceiling surfaces are composed of noncombustible materials. A CO_2 total flooding system allows for the selective termination of a test. These protective measures have resulted in a durable test article, which has withstood hundreds of tests with only minor damage and thus allowed for the conduct of parametric studies with different materials or different fire test conditions.

The test article is extensively instrumented to measure the major hazards produced by a cabin fire as a function of time at various cabin locations. The following measurements are routinely taken: temperature, heat flux, smoke density, carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), acid gases (e.g., hydrogen fluoride (HF), hydrogen chloride (HCl)), and organic gases (e.g., hydrogen cyanide (HCN)). Video and photographic coverage documents the visual progress of the fire.

The C-133 test article was utilized to evaluate candidate blocking layer materials under test conditions representative of the three major types of cabin fires. Figure 2 illustrates the installation of interior materials in the forward part of the test article. The furnished test section is centered at the fuselage opening (test station 140) adjacent to an external fuel fire used in postcrash studies. For the postcrash test condition, an additional opening is provided at test station 880 (figure 1). A large fan behind the fire pan can be employed to simulate ambient wind and create penetration of fuel flames through the forward opening. Under both the ramp and in-flight test conditions, all fuselage openings are closed. For the in-flight condition, a ducting system was designed and installed in the test article to simulate ceiling air intake and baseboard air exhaust from a cabin environmental control system. One cabin air change occurs approximately every 3 minutes. No ventilation was used under the ramp fire condition.

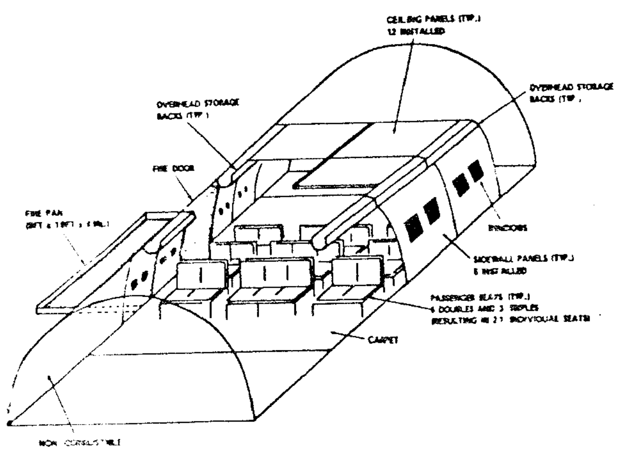


Figure 2. Installation of Wide-Body Materials Inside C-133 Test Article

During some of the tests only aircraft seats were subjected to the fire conditions (e.g., ramp and in-flight tests). This was necessary because of the great expense of the ceiling and sidewall panel materials and stowage bins. The seating configuration was always centered at test station 140.

IGNITION SOURCES

Table 2 lists the ignition sources used to evaluate the effectiveness of the candidate blocking layer materials. The plastic trash bag used in the ramp fire test was suggested by the 727 ramp fire discussed previously. Various ignition source intensities possible during an in-flight fire were employed, ranging from the relatively weak cigarette ignition to the more intense flight bag or gasoline fire. The burning flight bag ignition source, which was located underneath a seat, was also representative of floor burn through from a lower compartment. The most severe ignition source was the 80-square-foot fuel fire adjacent to a 76-inch by 42-inch fuselage opening, used to simulate a postcrash fire condition. Previous work had demonstrated that the intensity of the thermal radiation passing through an opening of this size was approximately 80 percent of the level produced by an infinitely large fuel fire under zero wind conditions (references 7 and 12).

Table 2. Test Ignition Sources

Type of Fire	Ignition Source
Ramp	. Plastic trash bag filled with approximately 18 ounces of paper towels and newspaper
In-Flight	. Cigarette . Newsprint (4 double sheets) . Gasoline (1 print) . Simulated nylon flight bag (contents 2 shirts and 2 double sheets of newsprint approximately 22 ounces)
Postcrash	. Jet fuel (80-square-foot pan containing 50 gallons of fuel)

TEST RESULTS

RAMP FIRE - In the ramp fire tests, three rows of triple aircraft seats, with each row containing two sets of triple seats and a section of carpet under the center row, were installed in the test article. The trash bag was placed adjacent to an outer seat in the middle row and ignited with a match. Figure 3 compares results for a test with unprotected cushions and a test with cushions protected with an LS-200 blocking layer. The results demonstrated that the use of a foam blocking material on seat cushions can prevent a ramp fire which would become out of control in 3 to 5 minutes, if the seats were not protected.

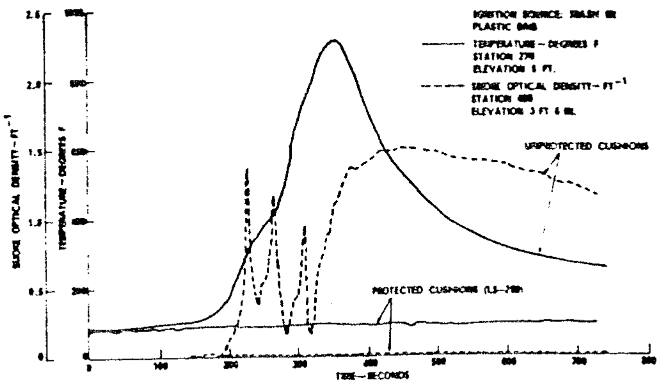


Figure 3. Seat Cushion Blocking Layer Benefit--Ramp Fire Scenario

Figure 3 indicates that the target seat became significantly involved in fire in about 3 to 3 1/2 minutes. By almost 6 minutes oxygen depletion caused the flames to subside and the fire to transition to a smouldering stage, evidenced by the temperature peak and subsequent decrease in temperature and by the persistent increase in smoke level. Although not shown in the figure, the seats reignited into a flaming mode when a door to the test article was opened, because the supply of oxygen in the cabin was replenished. Eventually, all 6 sets of triple seats were consumed by fire.

IN-FLIGHT FIRE (C-133) - The in-flight fire test setup was identical to that used in the ramp fire tests with two exceptions: (1) simulated cabin air ventilation was employed, and (2) the ignition source was placed under (versus adjacent to) the target seat (same seat location). Figure 4 compares the temperature history slightly

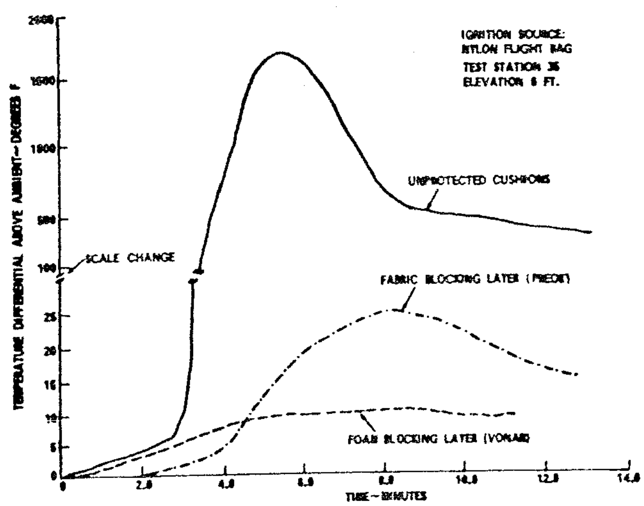


Figure 4. Seat Cushion Blocking Layer Benefit--In-Flight Scenario

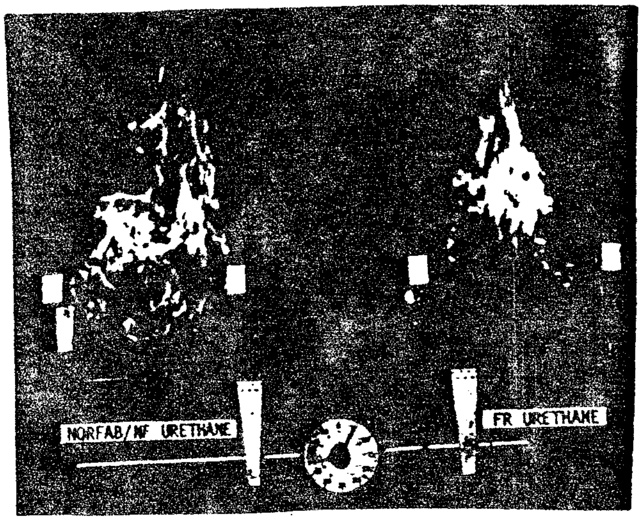
forward of the fire origin in tests with foam blocking layer protection, fabric blocking layer protection and no seat protection. Both types of blocking layer materials prevented a fire which would have spread uncontrolably without seat protection. Based on the peak temperatures, the foam blocking layer was more effective than the fabric blocking layer, although both types of material prevented fire spread beyond the vicinity of the ignition source.

The ramp and in-flight test results were similar in terms of the time interval from ignition to a significant increase in cabin temperature — approximately 3 minutes in both cases. This finding was probably due to the weights of the ignition sources being nearly equivalent. However, the in-flight ignition source was observed to continue burning for a longer time than the ramp fire ignition source. From figure 4, it appears that the in-flight source fire persisted for 8 minutes, apparently because of the slower-burning clothing materials.

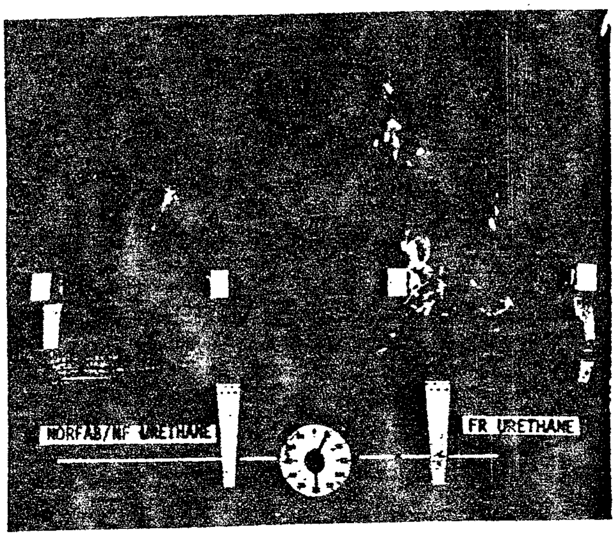
From a practical viewpoint, the time interval before significant seat involvement, without blocking layer protection, under most circumstances would be adequate for cabin crewmembers to extinguish the fire with hand-held extinguishers. Fires of this nature can be extinguished in 5 to 10 seconds under optimum firefighting conditions (e.g., immediate agent application, unobstructed access to base of fire, etc.). However, extenuating circumstances such as panic, or perhaps the fire origin being beneath the cabin floor, suggest the potential benefits of additional protection.

EFFECT OF FLAME RETARDANT IN URETHANE - In this period of unpredictable fuel costs, airplane operators continually strive for weight reduction. When a blocking layer material is employed, an increase in seat weight will be incurred. One method of minimizing the potential weight penalty of fire blocking layers is to utilize a nonfire-retardant (NF) urethane foam cushion, which is about 20 percent lighter than fire-retardant (FR) urethane foam. A series of tests were performed to determine if the use of a blocking layer over NF urethane foam presented any greater in-flight fire hazard than presently used FR urethane foam. Tests were also performed to study and compare the behavior of FR cushions with various blocking layers.

The tests were conducted in an open test bay area using a single aircraft triple seat (reference 13). The middle seat cushions were removed and the outer seats were configured in accordance to the comparison under study; e.g., in one test, both seats were protected with a foam blocking layer, but an NF foam was used in one seat and an FR foam in the other. For a given test, each seat was subjected to an identical ignition source. Figure 5 shows test results with newspaper ignition on the seat, with one seat comprised of an NF urethane foam protected with a fabric blocking layer and the other seat comprised of unprotected FR urethane foam. At 90 seconds, the protected seat had self-extinguished, while the unprotected seat fire was essentially out of control.



(t = 15 seconds)



(t = 90 seconds)

Figure 5. Seat Performance Against Newspaper Fire

Table 3 is a generalization of the in-flight ignition source results. It is apparent that either foam or fabric blocking layers over NF urethane cushions can prevent in-flight fires, which if left uncontrolled, can spread beyond the ignition source when the cushion is simply FR urethane. Moreover, when a blocking layer material is utilized, the presence or not of fire retardants in the urethane foam cushion will not have a bearing on the ultimate result, which is self-extinguishment of the seat fire. During replicate tests with blocking layer materials, the time to self-extinguishment depended on whether other seat components (e.g., armrest, tray back) were ignited. If these components were not involved, the fire was essentially out after the ignition source was consumed. When the seat components became involved, the fire burned, appreciably longer before self-extinguishing. During this latter kind of behavior, the fire intensity and growth was subdued compared to the burning of an unprotected seat. Thus, blocking layer materials were effective even when seat components other than the cushions were ignited.

Table 3. Generalization of Small Ignition Source Results

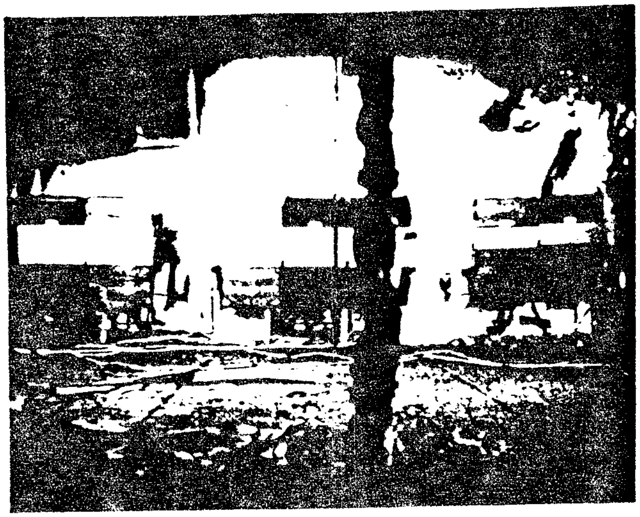
	Blocking Layer Type				
	None	Foam		Fabric	
	Urethane Foam Treatment				
Ignition Source	FR	FR	NF	FR	NF
Cigarette	Self-Extinguished	Self-Extinguished	Self-Extinguished	Self-Extinguished	Self-Extinguished
Newspapers on Seat	Destroyed Seat	Self-Extinguished	Self-Extinguished	Self-Extinguished	Self-Extinguished
Newspapers under Seat	Destroyed Seat	Self-Extinguished	Self-Extinguished	Self-Extinguished	Self-Extinguished
Gasoline (1 pint)	Destroyed Seat	Self-Extinguished	Self-Extinguished	Self-Extinguished	Self-Extinguished

FR Fire-Retardant
NF Nonfire-Retardant

POSTCRASH FIRE (FULL-SCALE TESTS) - The postcrash fire tests were the most realistic undertaken. In these tests, a section of the C-133 test article was realistically lined and furnished with surplus or new wide-body materials, as illustrated in figure 2 and reference 7. The main objective was to examine the postcrash fire benefit of seat cushion blocking layer materials within the context of the remaining interior materials. The materials were subjected to a zero wind fuel fire adjacent to a large (22 ft^2) fuselage opening. Prior testing had demonstrated that a zero wind condition would produce minimal cabin hazards from the fuel fire; therefore, any hazards detected with interior materials installed could be attributed to the burning materials. Four full-scale tests were conducted with the only variable being the cushion makeup. The following cushions were tested: (1) unprotected (FR urethane) cushion, (2) FR urethane cushion with foam (Vonar) blocking layer, (3) FR urethane cushion with fabric (Norfab®) blocking layer, and (4) noncombustible (ceramic fiber glass) cushion.

In each of the tests, the fuel fire ignited the interior and produced a condition called "flashover," which occurred at a different point in time in each test. Flashover corresponds to a rapid growth of the fire from an area in the immediate vicinity of the fuel fire to the remaining cabin interior.

Figure 6 is a set of photographs taken at 5-second intervals, evidencing the onset of flashover in the test with unprotected cushions.



(a) 2:05

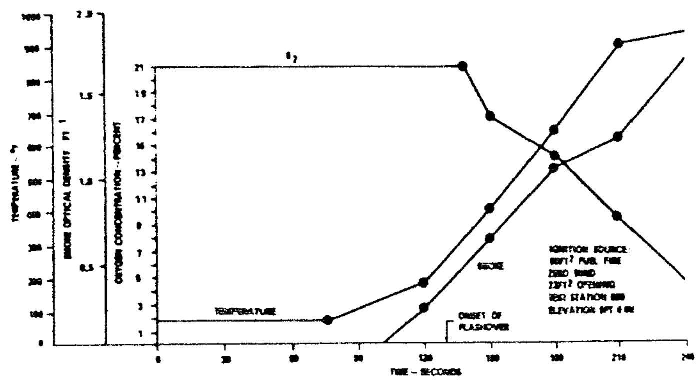
(b) 2:10

(c) 2:15

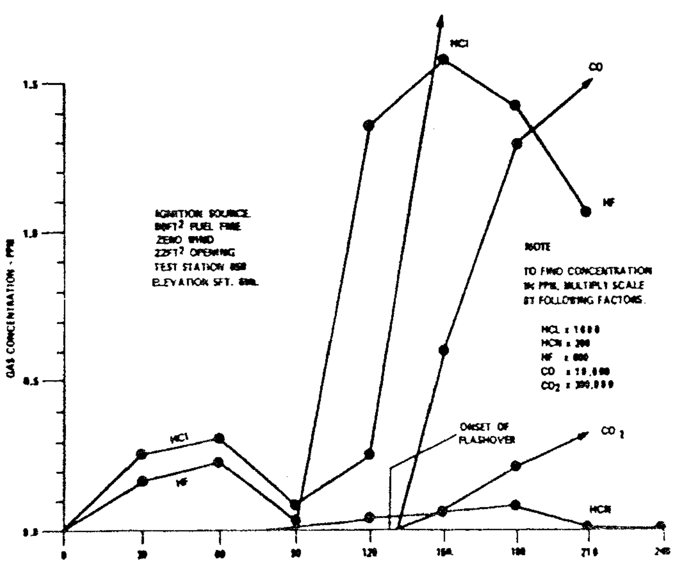
Figure 6. Photographic Documentation of Flashover

In a cabin fire, flashover seems to be caused by ignition of the hot smoke layer in the upper part of the cabin and of any materials nearby, leading to increased thermal radiation upon, and ignition of, materials in the lower cabin, and by burning ceiling panels which happen to fall upon and ignite seats.

In the C-133 test article, measurements are taken of what are believed to be the major fire hazards. Figure 7 contains these measurements as a function of time at an aft location for the test with unprotected cushions. Reference 7 contains an analysis which concludes that the various hazards are survivable before the onset of flashover, although widely accepted data does not exist for the incapacitation tolerance limits of the irritant gases HCl and HF. After flashover the various hazards increase markedly, and the analysis in reference 7 indicates that the tolerance limit is exceeded for five of the hazards. Thus, the occurrence of flashover indicates that conditions will rapidly become nonsurvivable throughout the cabin.



(a) During a Postcrash Fire



(b) During a Postcrash Fire

Figure 7. Hazards in Aft Cabin Produced by Burning Interior Materials

In order to quantitate the hypothetical survival time, a simple human survival model was developed which considers the effects of elevated temperature, CO_2, CO, HCN, HF, and HCl (reference 7). The major assumptions were that the hazards are additive and that a classical hyperbolic relationship exists between gas concentration and time of incapacitation. The model is hypothetical, and was developed as a tool for reducing a number of somewhat abstract hazard measurements into a single, cogent parameter-survival time.

The model was applied to analyze the survivability associated with the four full-scale fire tests with different cushion makeups. In the model, a variable called the mixture fractional effective dose (FED) is defined. It is calculated at each time increment analyzed, and is essentially the sum of the ratios for each hazard of measured dose to the incapacitation dose. Thus, the hypothetical survival time corresponds to that point in time when FED = 1.0.

Figure 8 is a plot of the calculated FED versus time in the aft cabin for the four full-scale fire tests. This plot indicates the safety benefit, in terms of increase in survival time, associated with seat blocking layer materials under the postcrash fire condition tested. The calculated FED does not include the effect of HCl in any of the tests because a malfunction in the analysis of HCl in one of the tests. The safety benefit of Vonar and Norfab blocking layer materials — 60 and 43 seconds, respectively — is considered significant, especially since the benefit is incurred within the context of the remaining interior materials. In addition, the results indicate that the amount of protection provided by Vonar is nearly equivalent to that of a noncombustible cushion, under the fire conditions studied. (Note that the improvement in survival time with the noncombustible cushions was only 8 seconds better than with the Vonar protected cushions.) The shape of the FED profiles indicate to some degree the rapidity by which conditions become nonsurvivable after the onset of flashover. In fact, the calculated safety benefit (survival time increase) for each of the protected cushion tests corresponds to the increase in time before the onset of flashover relative to the unprotected cushion test. Figure 8 also indicates that FED = 0 throughout the time framework of interest when the interior is noncombustible. This finding indicates that potential safety benefits exist, beyond that provided by seat blocking layers, by making improvements in the fire performance of other important interior materials; e.g., ceiling panels and overhead stowage bins.

Smoke was not a component of the human survival model. However, the impact of visibility obscuration resulting from smoke was calculated (reference 7). Figure 9 is a plot of cabin visibility in the aft cabin versus time for the four full-scale material tests. The most striking feature of the curves is the rapidity by which visibility becomes obscured, e.g., in some cases visibility was reduced from the length of the cabin to less than the width of the cabin in approximately 15 seconds. Also, by comparing figures 8 and 9, it is apparent that smoke becomes an important factor anywhere from 30 to 60 seconds before survival is no longer theoretically possible. This comparison also reveals that the ranking of results from best to worst for visibility loss was identical to the rankings for loss in survival time (i.e., noncombustible cushions > Vonar > Norfab > unprotected cushions).

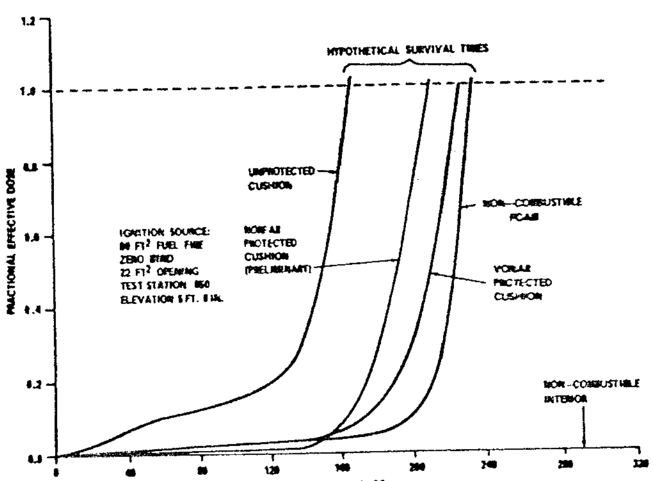


Figure 8. Effect of Cushioning Protection on Calculated Survival time Under Full-Scale Postcrash Fire Conditions

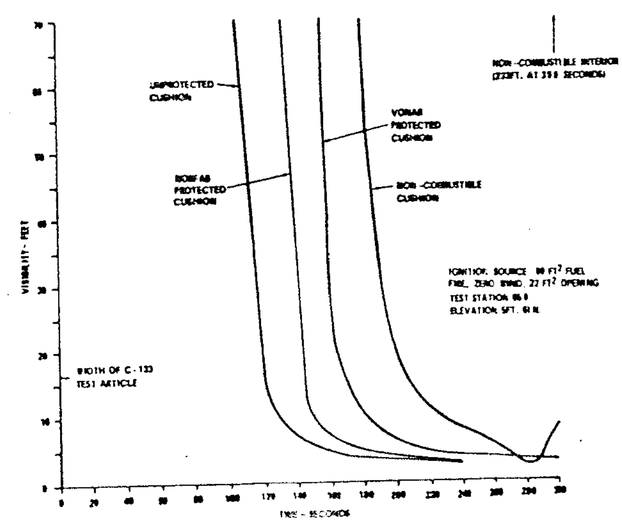


Figure 9. Effect of Cushioning Protection on Calculated Visibility Through Smoke Under Full-Scale Postcrash Fire Conditions

POSTCRASH FIRE (OTHER SCENARIOS) - The postcrash fire scenario discussed above was conceived for the purpose of creating a realistic impact-survivable fire situation wherein burning cabin materials have a dominant, if not controlling, effect on survivability. Obviously, a large number of other, and, perhaps more likely survivable postcrash fire conditions are possible. Another condition studied was a 2-foot-square opening, simulating a small fuselage rupture above the cabin floor, adjacent to the large external fuel fire. Because of the small rupture area, a simulated 3 miles per hour (mph) wind was utilized to intensify the cabin exposure conditions. Four double seats — three outboard and one inboard — symmetrically placed about the small rupture, were tested under these conditions. No other materials were placed in the test article. Figure 10 displays the cabin temperature history for three types of seating materials and for the fuel fire without seats. The results exhibit data crossover and small discrimination in the performance of different materials. For these reasons, this scenario was not utilized except for the above tests. The data also demonstrates that wind conditions created significant fuel-fire hazards inside the cabin. Under the conditions tested, approximately 50 percent of the cabin hazards were caused by the fuel fire.

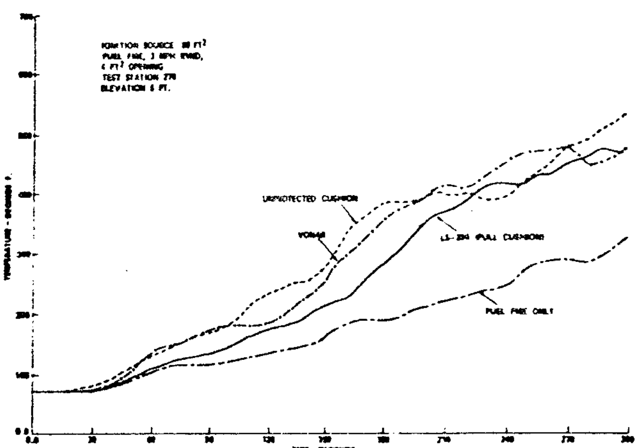


Figure 10. Postcrash Fire Test Results With Small Fuselage Opening and Wind

Another possible postcrash fire scenario consists of an intact fuselage with a door opening adjacent to a large external fuel fire. This scenario was also studied briefly, and is very similar to a past accident (reference 14). In these tests, a single triple outboard seat was located fore and aft of the type A door opening, and a 1.5 mph simulated wind was employed to create slight flame penetration into the cabin. Figure 11 compares temperature and smoke histories in tests with Vonar protected cushions and with unprotected cushions. In the test with protected cushions, the seat fire damage was minor and confined to the seat upholstery cover and various seat components; the flammable urethane foam did not become involved. By contrast, in the test with unprotected cushions, the fire became out of control in 3 to 4 minutes.

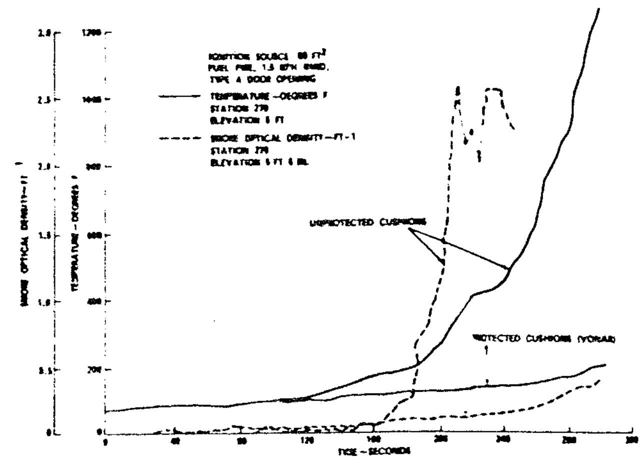


Figure 11. Seat Cushion Blocking Layer Benefit—Postcrash Fuel Fire Adjacent to Open Door

Thus, under this fire scenario, the benefit of seat cushion blocking layers is significant. An analysis of the results acquired for the three postcrash fire scenarios, as presented in figures 8, 10, and 11, demonstrate that potential benefits of seat cushion fire blocking layer materials are highly dependent upon fire scenario.

SUMMARY OF SIGNIFICANT FINDINGS

Based on the realistic cabin fire tests and analysis described in this paper, and on the seat cushion blocking layer materials evaluated and the types of fire test conditions employed, the following are the significant findings:

(1) Seat cushion fire blocking layer materials such as neoprene foam or aluminized high-temperature fabrics can prevent ramp and in-flight fires which become out of control when initiated at an unprotected seat and left unattended.

(2) Seat cushion fire blocking layer materials can significantly increase the safe time available for evacuation during specific types of postcrash cabin fire scenarios.

(3) Under severe fire conditions, such as a postcrash fuel fire, neoprene foam materials are more effective seat cushion blocking layers than aluminized high-temperature fabrics.

(4) Fire-retardant urethane foam can be replaced by nonfire-retardant urethane foam in aircraft seat cushions covered with a blocking layer material without essentially any loss in in-flight fire protection.

REFERENCES

1. "Fire Research on Cellular Plastics: The Final Report of the Products Research Committee," Library of Congress Catalog Card Number: 80-83306, April 1980.

2. "Final Report on the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee," Federal Aviation Administration, Volume I, Report FAA-ASF-80-4, June 26, 1980.

3. "Bi-Monthly Fire Record," Fire Journal, Vol. 74, No. 2, p. 22, March 1980.

4. "Aircraft Accident Report: Saudi Arabian Airlines, Lockheed L-1011, HZ-AHK, Riyadh, Saudi Arabia, August 19, 1980," Presidency of Civil Aviation, Jeddah, Saudi Arabia, January 16, 1982.

5. "Special Study: U.S. Air Carrier Accidents Involving Fire, 1965 through 1974, and Factors Affecting the Statistics," National Transportation Safety Board, Report NTSB-AAS-77-1, February 17, 1977.

6. Eklund, T.I. and Sarkos, C.P., "The Thermal Impact of External Fuel Fires on Aircraft Fuselages, Journal of Fire and Flammability, Vol. II, pp. 231-240, July 1980.

7. Sarkos, C.P., Hill, R.G., and Howell, W.D., "The Development and Application of a Full-Scale Wide Body Test Article to Study the Behavior of Interior Materials During a Postcrash Fuel Fire," AGARD Lecture Series No. 123 on Aircraft Fire Safety, AGARD-LS-123, June 1982.

8. Morford, R.H., "The Flammability of Neoprene Cushioning Foam," Journal of Fire and Flammability, Vol. 8, pp 279 - 299, July 1977.

9. Kourtides, D.A. and Parker, J.A., "Test Methodology for Evaluation of Fireworthy Aircraft Seat Cushions," Journal of Fire and Flammability, Vol. 15, pp. 56 - 76, January 1982.

10. Schutter, K.J. and Duskin, F.E., "Study for the Optimization of Aircraft Seat Cushion Fire Blocking Layers - Full Scale - Test Description and Results," NASA Contractor Report, Contract NASA2-11905, Douglas Aircraft Company, Report No. MDC J2525, May 1982.

11. Hill, R.G., Johnson, G.R., and Sarkos, C.P., "Postcrash Fuel Fire Hazard Measurements in a Wide-Body Aircraft Cabin," Federal Aviation Administration, NAFEC, Report FAA-NA-79-42, December 1979.

12. Eklund, T.I., "Pool Fire Radiation through a Door in a Simulated Aircraft Fuselage," Federal Aviation Administration, NAFEC, Report FAA-RD-78-135, December 1978.

13. Hill, R.G., et al, "Aircraft Seat Fire Blocking Layers; Effectiveness and Benefits Under Various Fire Scenarios," Federal Aviation Administration, report to be published.

14. "Aircraft Accident Report: Continental Air Lines, Inc., McDonnell-Douglas DC-10-10, N68045, Los Angeles, California, March 1, 1978," National Transportation Safety Board, Report NTSB-AAR-79-1, January 25, 1979.

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Evaluation of Aircraft Interior Panels Under Full-Scale Cabin Fire Test Conditions

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EVALUATION OF AIRCRAFT INTERIOR PANELS UNDER FULL-SCALE CABIN FIRE TEST CONDITIONS

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Abstract

Realistic full-scale fire tests demonstrated the potential safety benefits of advanced interior panels in transport aircraft, and displayed the characteristics of cabin fire hazards. The tests were conducted in a C-133 airplane, modified to resemble a wide-body interior, under postcrash and in-flight fire scenarios. The safety benefit of the advanced panel ranged from a 2-minute delay in the onset of flashover when the cabin fire was initiated by a fuel fire adjacent to a fuselage rupture, to the elimination of flashover when the fuel fire was adjacent to a door opening or when an in-flight fire was started from a seat drenched in gasoline. Analysis of the cabin hazards measured during postcrash fire tests indicated that the greatest threat to passenger survival was cabin flashover, and that toxic gases did not reach hazardous levels unless flashover occurred.

Introduction

Objective

The primary objective of this paper is to describe the safety benefits of advanced interior panels under realistic full-scale aircraft cabin fire test conditions. A secondary objective is to characterize and analyze the hazards affecting occupant survivability in cabin fires.

Background

Although the accident record of the airline industry is excellent, on rare occasions accidents do occur with grave consequences. Fire is a major concern because of the large quantities of flammable fuel carried by the airplane and because of the cabin design, which consists of a densely populated enclosure lined and furnished with polymeric materials. For the United States (U.S.) airline industry, an average of 32 fatalities per year are attributable to fire. [1] All of these fatalities have occurred in crash accidents which are usually accompanied by the spillage and ignition of jet fuel. In spite of the intensity and apparent dominance of a jet fuel fire, under certain accident conditions, the survivability of cabin occupants will be established by the hazards of burning interior materials. [2] The Federal Aviation Administration (FAA) is supporting and conducting research, testing, and development to minimize the hazards of burning interior materials in the postcrash fire environment. [3] Also, the in-flight fire problem is now receiving more attention because of this type of accident experience with foreign carriers; e.g., Air Canada DC9 accident in Cincinnati. [4]

Improvements for two important types of cabin interior materials have been investigated — seat cushions and panels. Foremost was the work on seat cushions. Because of the flammable nature of urethane foam cushions, a fire blocking layer concept was developed that provides significant safety benefits for both postcrash and in-flight cabin fires. [5] The FAA has proposed more stringent flammability regulations for seat cushions that would result in the installation of fire blocking layer materials within a 3-year period. [6] The current emphasis by FAA is to develop improved test requirements and materials for interior panels, which constitute the sidewalls, ceiling, stowage bins, and partitions of a contemporary transport cabin interior. The importance of panels during a cabin fire stems from their large surface area and location in the upper cabin (ceiling, stowage bins) where fire temperatures are highest.

Generally, interior panels are composite structures composed of a honeycomb core, resin-impregnated cloth facings and a decorative laminate. Over the past 10 years, the National Aeronautics and Space Administration (NASA) has developed and evaluated improved panel component materials. The main approach has been to increase the anaerobic char yield in order to improve fire performance. [7] Currently, emphasis is on the development of an advanced resin system for lightweight facings, which meets fabrication, mechanical property and service performance requirements, and exhibts superior fire properties compared to in-service materials. [8]

Fire performance of polymeric materials is usually gauged on the basis of small-scale laboratory tests. A large number of fire tests with a variety of end points are available. It is generally recognized that these small-scale test results, a priori, cannot predict the performance of a material in a real fire. Therefore, full-scale fire tests are necessary to determine the potential safety in real fires and to corroborate the trends indicated by small-scale test results. During full-scale tests, important real-world conditions such as fire source, geometry, and scale are reasonably simulated.

Another important application of full-scale fire tests, is for the analysis of the hazards affecting survivability during a cabin fire. Usually, the hazards of an enclosure fire, such as a fire inside an aircraft cabin, are grouped into three categories: heat, smoke (visibility), and toxic gases. What is the relative importance of each of these hazards? What are the effects of different types of fire scenarios on the significance of each hazard category? Realistic full-scale tests can provide information which, at the very least, give insight for answering these complex and far-reaching questions.

Discussion

Interior Panel Materials

Figure 1 describes the advanced and in-service panels evaluated in this paper. The test samples were cut from flat sheets made of 1/4-inch thick honeycomb core that were especially fabricated for this study. NASA selected the individual components of the advanced panel design primarily on the basis of optimizing fire performance, and minimal consideration was given to mechanical, service, and processing requirements. The goal was to establish a benchmark for advanced panel fire performance, at this time, irrespective of other practical considerations. The in-service panel contained epoxy/fiberglass facings and represented the type of panel design employed in the earliest wide-body jet interiors.

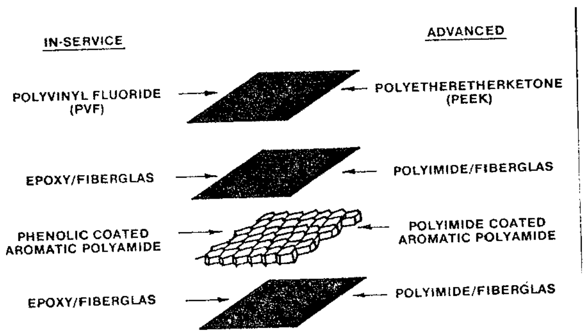

FIGURE 1. COMPOSITION OF COMPOSITE PANELS

Polyimide was selected in the advanced panel design for facing resin and core coating because of its higher degradation temperature and greater anaerobic char yeild compared to epoxy resin. For example, a typical degradation temperature for commercial epoxy and polyimide resin was 500° C and 620° C, respectively. [9] Polyetheretherketone (PEEK) was selected as the decorative film in the advanced panel design, primarily to eliminate the production of hydrogen fluoride during thermal decomposition of the polyvinyl fluoride film commonly used in contemporary panels. The superior thermal stability of the advanced panel was evidenced alone by its cure temperature; viz., 500° F for 16 hours vs. 350° F for approximately 2 hours for the in-service panel.

Small-Scale Test Results

The advanced and in-service panels were initially characterized using standardized small-scale fire tests (table 1). All test methods were American Society of Testing and Materials (ASTM) standards, including the vertical Bunsen burner test method prescribed by FAA under Federal Aviation Regulation (FAR) 25.853. [10] Generally, the advanced panel was better than the in-service panel for all test measurements and gave remarkable results; e.g., no visible smoke, a limiting oxygen index of 69, and a burn length of less than one-inch (FAR 25.853a allows a burn length of six inches). Nevertheless, the results obtained with the in-service panel were excellent by most standards, although consistently inferior to the advanced panel. For example, the limiting oxygen index, which essentially is the minimum concentration of oxygen to allow for ignition by a small pilot flame, was 42 percent for the in-service panel, or double the normal oxygen concentration in air. Similarly, a flame spread index (I_s) of two was well within the design goal of a major airframe manufacturer and was easily compliant with guidelines established for rapid rail vehicles. The test method which provided the greatest discrimination between the advanced and in-service panels was the Ohio State University (OSU) rate of heat release apparatus (a difference in heat output of approximately a factor of 15 was measured). This finding was encouraging in that FAA is currently examining the OSU apparatus as a potential improved fire test method for cabin interior materials. [3]

TABLE 1. SMALL-SCALE TEST RESULTS

TEST METHOD	MEASUREMENT	IN-SERVICE	ADVANCED
VERTICAL BUNSEN BURNER (FAR 25.853A)	BURN LENGTH, IN.	3.0	0.8
	FLAMING TIME, SEC.	3.0	0.0
RADIANT PANEL (ASTM E-162)	I_s	2	<1
NBS SMOKE CHAMBER (ASTM E-662)	Ds AT 90 SEC.	20	0.0
	Ds AT 4 MIN.	20	0.0
LIMITING OXYGEN INDEX (ASTM D-2863)	O_2 (%) CONC.	42	69
OSU RATE OF HEAT RELEASE* (ASTM E-906)	PEAK HEAT (KW/M^2)	66	4.2
	TOTAL HEAT ($KW\text{-}MIN/M^2$)	116	7.3

*5W/CM², PILOTED

Test Article

The full-scale test article was a C-133 aircraft, modified to resemble a wide-body cabin interior, as shown in figure 2 and reference 2. The cross sectional area is similar to, although slightly smaller than, a wide-body cabin. An interior volume of 13,200 ft^3 is representative of a wide-body jet.

The floor, walls, and ceiling of the test article are composed of, or lined with, noncombustible materials (all combustible materials in the original cargo aircraft were removed). A CO_2 total flooding system allows for the selective termination of a test. These protective measures have resulted in a durable test article, which has withstood hundreds of tests and requires only periodic repairs in the intense fire areas.

The test article is extensively instrumented to measure the major hazards produced by a cabin fire as a function of time at various cabin locations. The following measurements are routinely taken: temperature, heat flux, smoke density, and concentration of carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), hydrogen chloride (HCl), hydrogen fluoride (HF), and hydrogen cyanide (HCN). Video and photographic coverage document the visual progress of the fire.

The C-133 test article was utilized to compare the performance of the advanced and in-service panels installed in a representative cabin interior layout as sidewalls, stowage bins, ceiling and partitions, under simulated postcrash and in-flight fire conditions. Under the post-crash scenarios, the interior was subjected to an external fuel fire adjacent to an opening (door or fuselage rupture) in the forward part of the fuselage (figure 2). An additional door opening existed in the rear of the fuselage to simulate an opened exit for passenger evacuation. For the in-flight fire scenario, the fuselage openings were covered and a perforated ducting system simulated the ceiling discharge of air into the cabin as occurs with the cabin environmental control system (ECS). A measured cabin air change occurred every 3 minutes. For both types of scenarios, the panels were installed around the fire door (station 140) in a symmetrical manner (see later discussion).

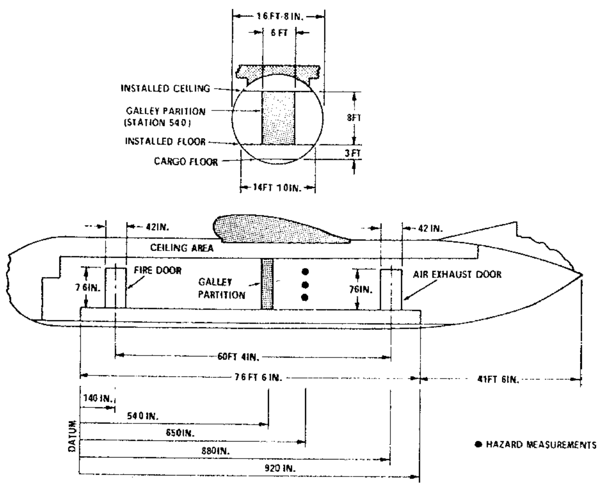

FIGURE 2. SCHEMATIC OF C-133 WIDE-BODY CABIN FIRE TEST ARTICLE

Fire Scenarios

Table 2 outlines the fire scenarios utilized in this study to compare the behavior of the advanced and in-service panels. In general, the postcrash scenarios consisted of an external fuel fire adjacent to a fuselage opening (door or rupture) whereas, the in-flight scenario consisted of a seat fire in a closed fuselage.

TABLE 2 FIRE SCENARIOS

NO.	DESIGNATION	TYPE	IGNITION SOURCE	FUSELAGE CONFIGURATION	VENTILATION
1	FUEL FIRE/ RUPTURE	POSTCRASH	FUEL FIRE	INTACT, TWO OPENINGS: RUPTURE (FIRE) DOOR (AFT)	NATURAL ZERO WIND
2	FUEL FIRE/ OPEN DOOR	POSTCRASH	FUEL FIRE	INTACT, TWO OPENINGS: DOOR (FIRE) DOOR (AFT)	NATURAL ZERO WIND
3	GASOLINE/ SEAT	IN-FLIGHT	SPILLED GASOLINE ON SEAT	CLOSED	CONTROLLED

In the postcrash scenario, previous work had demonstrated that the size of the C-133 external fuel fire produced 80 percent of the radiant heat flux into the interior expected from an infinite fire.[11] Thus, the experimental fuel fire gave a reasonable simulation of a large pool of burning fuel. The tests were conducted inside a large test facility under quiescent (zero wind) conditions. With an unfurnished C-133 interior and zero wind, there is virtually no accumulation of fuel fire hazards (temperature, smoke, and gases) inside the test article.[11] For this reason, the cabin hazards measured with interior materials installed and a zero wind fuel fire are attributed to burning materials, although fuel fire flames are drawn into the interior as the materials begin to ignite and burn.[12] The main role of the fuel fire is to subject the interior materials to intense radiant heat.

The in-flight fire scenario consisted of the ignition of a passenger seat doused with one quart of gasoline. It probably represented the most intense in-flight fire that is likely to occur out in the open (in contrast to a fire in a concealed area). The use of forced ventilation in a closed fuselage for the in-flight scenario was expected to affect the fire characteristics, compared to the postcrash case with fuselage openings and natural ventilation.

Test Results and Analysis

General Approach

The general approach was to compare the test results between the advanced and in-service panels for each of the three types of fire scenarios. A total of six full-scale tests were conducted, consisting of a single test with each type of panel for each fire scenario.

Postcrash Fuel Fire and Fuselage Rupture Scenario

The arrangement of materials with the post-crash fire scenario with a fuselage rupture adjacent to the fuel fire is shown in figure 3. Basically, a small area of the interior in the vicinity of the fuselage rupture was lined with the panels being examined and furnished with seats and carpet. The same type of seats and carpet were used for all the tests. The seats were surplus aircraft passenger seats protected with cushion fire blocking layers and the carpet was new, aircraft grade wool/nylon carpet. The quantity of materials employed was more than adequate to produce non-survivable conditions in the event of ignition and adequate fire growth. By using seats and carpet in addition to the panels being evaluated, the effect of panel flammability on the ignition and burning of other cabin materials used in large quantities, and vice-versa, was taken into consideration.

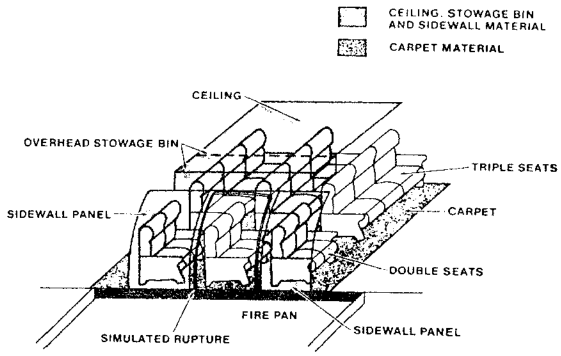

FIGURE 3. POSTCRASH FUEL FIRE/RUPTURE SCENARIO

The postcrash fuel fire scenario with a fuselage rupture was the most severe fire condition used, primarily because a seat was centered in the rupture and exposed to high levels of radiant heat. When that seat started to burn, it caused additional radiant heat to impinge upon the other interior materials. A flashover — defined in this paper as the sudden and rapid uncontrolled growth of the fire from an area in the immediate vicinity of the fuel fire to the remaining materials — occurred with both types of panels. However, the time to flashover was much earlier in the test with in-service panels than in the test with advanced panels. As shown in figure 4, the difference in flashover time, from the rapid rise of temperature measured by a thermocouple mounted 12 inches below the ceiling and near the fire door, was approximately 140 seconds. Since the occurrence of flashover is the event in a postcrash cabin fire that creates non-survivable conditions, as discussed later in this paper and in an earlier study (reference 2), the advanced panels also resulted in 140 seconds of additional time available for evacuation, or 150 percent more available evacuation time than with the in-service panels. This difference in available evacuation time was clearly a significant benefit to be gained from the advanced panels.

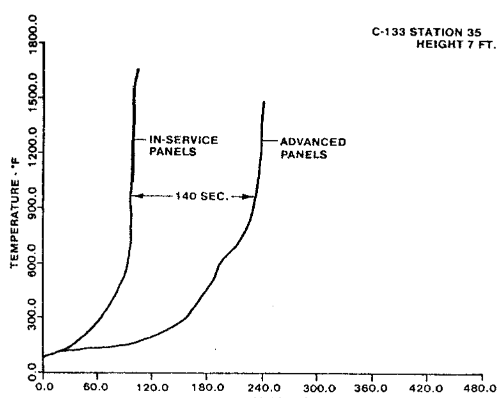

FIGURE 4. BENEFIT OF ADVANCED COMPOSITE PANELS-EXTERNAL FUEL FIRE/FUSELAGE RUPTURE SCENARIO

Postcrash Fuel Fire and Open Door Scenario

The arrangement of materials with the postcrash fire scenario with an opened door adjacent to the fuel fire is shown in figure 5. Materials placement was similar to the fuselage rupture scenario except that the center row of seats was eliminated and a box-like structure representing a galley was installed. The resultant fire condition was less severe than with the fuselage rupture scenario because of the removal of the passenger seat next to the opening.

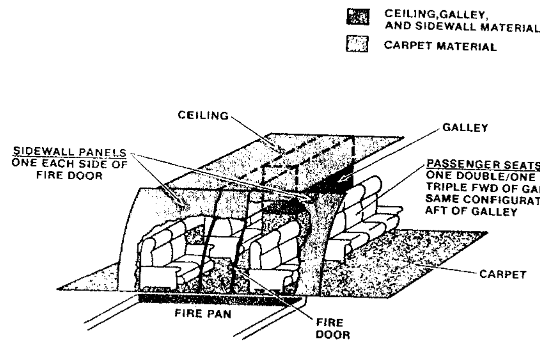

FIGURE 5. POSTCRASH FUEL FIRE/OPEN DOOR SCENARIO

The superior fire performance of the advanced panels was even more evident with the fuel fire/open door scenario. Under this scenario, the usage of advanced panels eliminated flashover. This result is demonstrated in figure 5, which compares the temperature history inside the test article for both types of panels. With in-service panels, flashover occurred in aproximately 2 1/2 minutes; however, with advanced panels, flashover did not occur over the 7-minute test duration. A comparison of the results with both types of postcrash scenarios (see figures 4 and 6) demonstrates the consistency of the data and illustrates that the rate of development of a cabin fire is largely dependent on fire scenario.

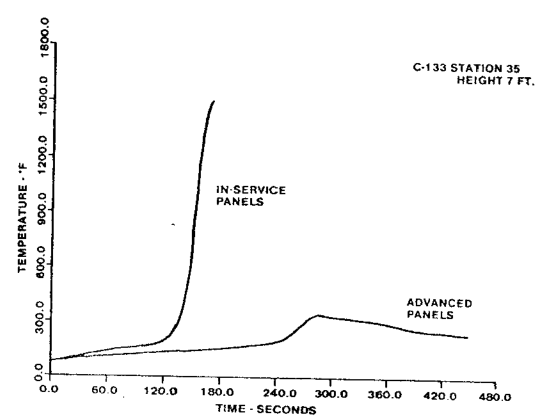

FIGURE 6. BENEFIT OF ADVANCED COMPOSITE PANELS - EXTERNAL FUEL FIRE/OPEN DOOR SCENARIO

An analysis of the cabin hazards measured in the fuel fire/open door test with in-service panels revealed the importance of flashover in dictating survivability during a postcrash cabin fire. This data is shown in figure 7, which contains the hazard histories measured approximately 40 feet aft of the fire door at an elevation of 5 feet 6 inches. The methods of analysis are described in reference 13. Before the flashover which occurred at approximately 150 seconds, the cabin environment was clearly survivable; after flashover, the conditions very suddenly deteriorated to such a degree that survival would have been highly unlikely. The suddeness of flashover, and perhaps the fact that it occurs without any apparent warning, may make passengers unaware of the imminent dangers that they face during a cabin fire. For example, within 30 seconds, as shown in figure 7, visibility decreased from about 30 feet to 3 feet, temperature measured from slightly above ambient to over 400° F, CO increased from zero to over 2500 ppm, and oxygen decreased from ambient to 16 percent. Therefore, it was concluded that improvements in postcrash cabin fire safety, when burning interior materials are the dominant factor, can be best attained by delaying the onset of flashover. If material selection is on the basis of state-of-the-art small-scale fire tests, then the use of an appropriate flammability test would seem to be far more beneficial than the use of either smoke or toxicity tests.

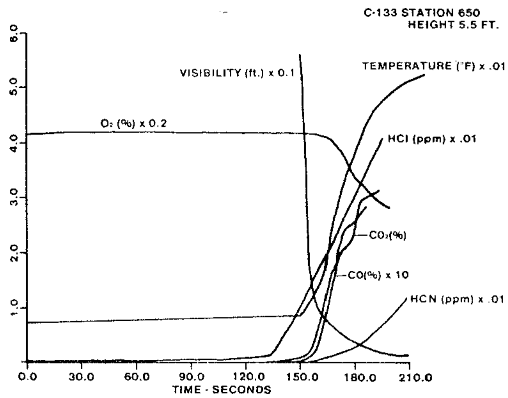

FIGURE 7. HAZARD TIME PROFILES WITH IN-SERVICE COMPOSITE PANEL - EXTERNAL FUEL FIRE/ OPEN DOOR SCENARIO

Why were the hazards measured 40 feet aft of the fire door at an elevation of 5 feet 6 inches virtually zero for over 2 minutes in the fuel fire/open door test with in-service panels? There are two likely reasons for this result. First, the small mass burning rate before flashover and the large cabin volume (13,200 cubic feet) made dilution and wall loss effects (heat transfer, adsorption) dominant. Secondly, the hazards that are produced before flashover are largely contained in the hot "smoke layer" which clings to the ceiling, above the measurement location and probably above the head of most passengers. Previous C-133 tests, [2], and the photographic/ video coverage from the tests described in this paper, document the significant stratification during a postcrash cabin fire with natural ventilation; i.e., with no forced ventilation.

Figure 8 also demonstrates that the hazards over this 7-minute test were clearly survivable. At 7 minutes, the temperature had only increased by 20° F over ambient, the concentration of CO_2 was 2000 ppm, the concentration of O_2 remained at ambient, and visibility had decreased to 50 feet. The toxic gases CO, HCl, HCN, and HF were not detected. This data also supports the conclusion that in a postcrash cabin fire, the hazards effecting survival are created by a flashover. Also, smoke and toxic gas hazards affecting survivability did not materialize as a consequence of flashover being prevented.

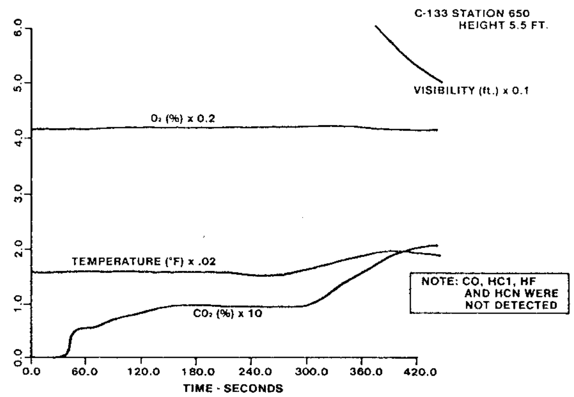

FIGURE 8. HAZARD TIME PROFILES WITH ADVANCED COMPOSITE PANELS EXTERNAL FUEL FIRE/ OPEN DOOR SCENARIO

In-Flight Fire Scenario

Figure 9 shows the arrangement of materials for the in-flight scenario. The placement of panels was identical to the fuel fire/rupture test, and two rows of double seats with cushion fire blocking layers were used. The fuselage openings were covered and a perforated duct simulated air discharge from the cabin ECS. The seat next to the covered door, doused with one quart of gasoline, served as the fire source. This type of seat fire will burn for 2 mnutes, with a peak burning rate at 40 seconds before self-extinguishing because of the fire blocking layer. [13]

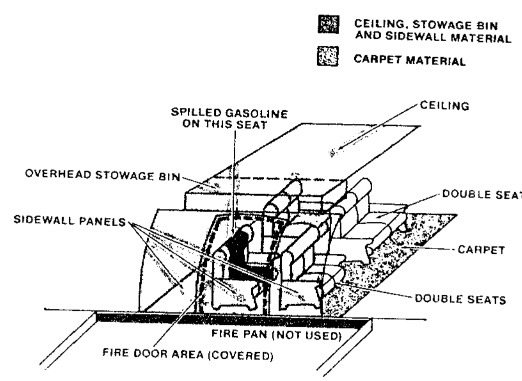

FIGURE 9. IN-FLIGHT GASOLINE/SEAT SCENARIO

The in-flight fire scenario was the least severe of the three scenarios studied. Figure 10 compares the temperature history near the fire source for the in-service and advanced panels. As in the fuel fire/open door test, flashover did not occur with the advanced panels. The fire resistance of the more flammable in-service panels was also sufficient to delay the onset of flashover until 8 minutes. From a practical viewpoint, an in-flight fire of this kind with in-service panels would, under most circumstances, have been extinguished by crewmembers utilizing hand-held extinguishers before the fire became out of control.

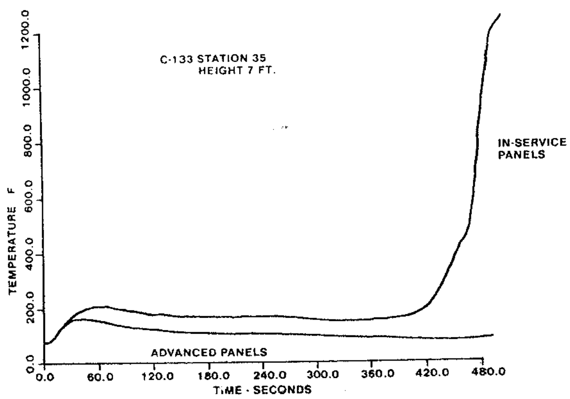

FIGURE 10. BENEFIT OF ADVANCED COMPOSITE PANELS - IN-FLIGHT FIRE SCENARIO

The controlled ventilation in the in-flight scenario tended to distribute the seat fire hazards throughout the airplane. Figure 11 presents the measured hazard histories, at a station located 40 feet aft the fire source at an elevation of 5 feet 6 inches, for the in-service panel test. Each of the measured hazards was detected before the onset of flashover, apparently because of the mixing action associated with the controlled ventilation. In contrast, for the postcrash tests where the cabin was ventilated naturally through fuselage openings, the hazards were primarily contained in the ceiling smoke layer, and remained virtually undetected at the 5-foot 6-inch sampling height until the cabin flashover (e.g., see figure 7). For the in-flight test, however, each measured hazard before flashover was well below its estimated incapacitation level. For example, at 8 minutes the calculated dose of CO was approximately 4000 ppm-minutes, which is significantly below the estimated human escape impairment dose of 30,000-40,000 ppm-minutes.[14] Also, the measured concentration of HCl, which was less than 100 ppm, would have been easily tolerated by passengers, based on recent primate studies.[14] The main peril before flashover was the dramatic loss in visibility due to smoke (calculated visibility was less than 10 feet at 30 seconds). Smoke obscuration may lead to panic and may impede fire control measures by the crew, especially if the smoke persists, as evidended by figure 11. It is interesting to note that significant smoke obscuration can occur without hazardous levels of toxic gases or elevated temperatures.

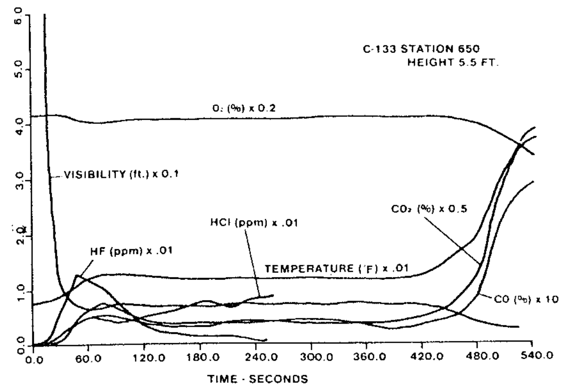

FIGURE 11. HAZARD TIME PROFILES WITH IN-SERVICE COMPOSITE PANELS - IN-FLIGHT FIRE SCENARIO

Figure 12 compares the calculated visibility for the advanced and in-service panel tests. With the advanced panel, smoke obscuration increased until the seat fire began to self extinguish and decreased thereafter as the smoke was exhausted by the controlled ventilation system. Smoke obscuration persisted throughout the in-service panel test because the seat fire spread to other cabin materials and eventually resulted in a flashover. Therefore, during an in-flight cabin fire the environmental control system can alleviate smoke conditions, provided that the concentrations are not excessive or the fire is brought under control.

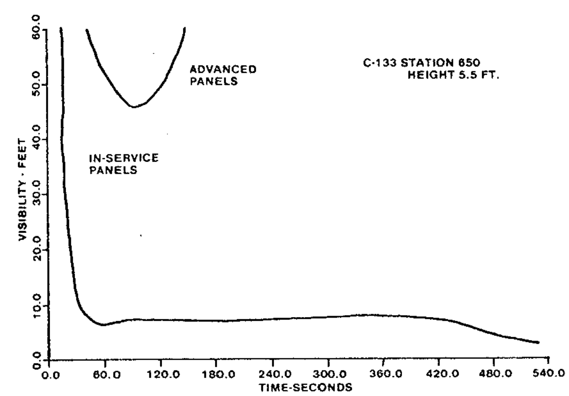

FIGURE 12. SMOKE VISIBILITY COMPARISON OF ADVANCED AND IN-SERVICE COMPOSITE PANELS - IN-FLIGHT FIRE SCENARIO

Summary of Significant Findings

Based on the realistic, full-scale cabin fire tests and analysis described in this paper, and on the composite panel materials evaluated and the types of fire scenarios employed, the following are the significant findings:

(1) Advanced interior panels can provide a significant safety improvement during postcrash and in-flight cabin fires.

(2) The greatest threat to passenger survival during postcrash cabin fires dominated by burning interior materials, is cabin flashover.

(3) Toxic gases produced during postcrash cabin fires consisting of a fuel fire adjacent to a fuselage opening or in-flight fires initiated by a gasoline-drenched seat fire do not reach hazardous levels unless flashover occurs.

(4) During an in-flight fire, the cabin environmental control system has a major effect on the distribution and dissipation of hazards.

References

1. Final Report of the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee, Federal Aviation Administration, Volume I, Report FAA-ASF-80-4, June 26, 1980.

2. Sarkos, C. P., Hill, R. G., and Howell, W. D., The Development and Application of a Full-Scale Wide-Body Test Article to Study the Behavior of Interior Materials During a Postcrash Fuel Fire, AGARD Lecture Series No. 123 on Aircraft Fire Safety, AGARD-LS-123, June 1982.

3. Engineering and Development Program Plan Aircraft Cabin Fire Safety, Federal Aviation Administration, Report FAA-ED-18-7, revised February 1983.

4. Aircraft Accident Report: Air Canada Flight 797, McDonell-Douglas DC-9-32, C-FTLU, Greater Cincinnati International Airport, Covington, KY, June 2, 1983, National Transportation Safety Board, Report NTSB/AAR-84/09, August 8, 1984

5. Sarkos, C. P., and Hill, R. G., Effectiveness of Seat Cushion Blocking Layer Materials Against Cabin Fires, SAE Technical Paper No. 821484, presentd at Aerospace Congress and Exposition, October 25-28, 1982.

6. Flammability Requirements for Aircraft Seat Cushions; Notice of Proposed Rulemaking, DOT/FAA, Federal Register, Volume 48, No. 197, p. 46251, October 11, 1983.

7. Parker, J. A., and Kourtides, D. A., Fireworthiness of Transport Aircraft Interior Systems, AGARD Lecture Series No. 123 on Aircraft Fire Safety, AGARD-LS-123, June 1982.

8. Parker, J. A., and Kourtides, D. A., New Fireworthy Composites for use in Transportation Vehicles, Journal of Fire Sciences, Vol. 1, No. 6, pp 432-458, November/December 1983.

9. Eklund, T. I., Quasi-Steady Analysis of Aircraft Panel Flammability, Federal Aviation Administration, Report DOT/FAA/CT-84/14, June 1984.

10. Airworthiness Standards; Transport Category Airplanes, DOT/FAA, Federal Aviation Regulations, Volume III, Part 25, Trasmittal 10, effective May 1, 1972.

11. Hill, R. G., Johnson, G. R., and Sarkos, C. P., Postcrash Fuel Fire Hazard Measurements in a Wide-Body Aircraft Cabin, Federal Aviation Administration, Report FAA-NA-79-42, December 1979.

12. Quintiere, J. G., and Tanaka, T., An Assessment of Correlations Between Laboratory and Full-Scale Experiments for the FAA Aircraft Fire Safety Program, Part 5: Some Analyses of the Postcrash Fire Scenario, National Bureau of Standards, Report NBSIR 82-2537, July 1982.

13. Hill, R. G., Brown, L. J., Speitel, L., Johnson, G. R., and Sarkos, C. P., Aircraft Seat Fire Blocking Layers: Effectiveness and Benefits Under Various Scenarios, Federal Aviation Administration, Report DOT/FAA/CT-83/43, February 1984.

14. Kaplan, H. L., Grand, A. F., Rogers, W. R., Switzer, W. G., and Hartzell, G. E., A Research Study of the Assessment of Escape Impairment by Irritant Combustion Gases in Postcrash Aircraft Fires, Federal Aviation Administration, Report DOT/FAA/CT-84/16, September 1984.

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1982

The Development and Application of a Full-Scale Wide Body Test Article to Study the Behavior of Interior Materials During a Postcrash Fuel Fire.

by
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Richard G. Hill
Wayne D. Howell

SUMMARY

Over the past 20 years, all fatalities attributable to fire in United States air carrier accidents have occurred during survivable crashes (versus in-flight fire accidents). In almost all of these cases, the postcrash cabin fire was initiated by a large fuel fire external to the aircraft. Under these conditions, the importance and role of cabin materials on survivability, in the context of and in contrast to a large fuel fire, is difficult to assess. Small-scale fire tests on cabin materials — by themselves — do not treat the dynamic range of conditions and important parameters present in a real cabin fire. Therefore, over the last 5 years, the Federal Aviation Administration (FAA) has placed increasingly more emphasis on large- and full-scale fire tests and fire modeling to understand and demonstrate the behavior of cabin materials in a postcrash fuel-fed fire.

The focal point of this work is a full-scale, wide-body test article, constructed from a surplus C-133 aircraft. This paper describes the following major elements of the development and application of the C-133 article to study postcrash cabin fires: (1) initial development, capabilities and instrumentation; (2) derivation of fuel fire test conditions based on physical modeling and large-scale fire tests; (3) characterization of cabin fire hazards arising solely from an external fuel fire without the contribution of interior materials; (4) characterization of cabin fire hazards resulting from the exposure of wide-body interior materials to an external fuel fire (the fires, by itself, would be clearly survivable over the test duration if the interior were noncombustible); and (5) evaluation of the effectiveness of urethane seat cushion fire blocking layers and improved cushioning materials over a range of test configurations. The results of the extensive tests that have been performed to date, especially over the past 12 to 18 months, are beginning to improve our understanding of the cabin hazards and important parameters associated with postcrash fire, and, by the example of seat cushions, illustrate how safety benefits can be realized by the usage of improved materials.

INTRODUCTION

OBJECTIVE

The objective of this paper is twofold: (1) describe the development and design of a full-scale test article for studying the characteristics of transport cabin fires created by a postcrash external fuel fire; and (2) describe the evaluation of the effectiveness of aircraft seat cushion fire blocking layers under large- full-scale test conditions.

BACKGROUND

Aircraft accident investigations, in most instances, do not furnish the detailed information required to identify the primary physical factors contributing to those fatalities resulting from fire. This lack of information is due, in part, to the infrequent occurrence of aircraft accidents and the usual destruction of evidence by the fire, but, more importantly, to the complex nature of the fire dynamics and hazards ultimately responsible for preventing escape by passengers and crewmembers. Therefore, although the outcome of an accident investigation may suggest the existence of a design deficiency leading to fire fatalities in a particular case, some form of controlled and well-instrumented experimentation is needed to validate the conclusions reached and the benefits of proposed improvements. The type of testing which is most convincing is that which most closely replicates the actual fire environment and aircraft geometry configuration; i.e., what has been termed a full-scale test. The utilization of full-scale tests is a major and integral aspect of the aircraft fire safety program conducted by the United States (U.S.) Federal Aviation Administration (FAA) (reference 1). This paper will describe the development and application of a full-scale cabin fire test article for studying the behavior of interior materials subjected to an external fuel fire.

A number of organizations, including the National Transportation Safety Board (NTSB), which has the responsibility for investigating civil aviation accidents in the United States, have analyzed the incidence of aircraft accidents accompanied by fire. A study by NTSB for the period 1965-1974 estimated that 15 percent of all fatalities in U.S. air carrier accidents were attributable to the effects of fire (reference 2). In all instances, the cause of the fire was the result of aircraft crash impact with the ground. Moreover, in most cases, the fire originated from the ignition of jet fuel released from fuel tanks damaged by the crash impact.

A much smaller number of fatal accidents have occurred in U.S. manufactured aircraft operated by foreign carriers as a result of accidental fire erupting inside the fuselage while the aircraft was in-flight. These in-flight fatal fires consist of a Varig 707 in 1974, a Pakistani 707 in 1979, and a Saudia L1011 in 1980, combining for a total of over 500 fatalities. As a consequence of the two recent accidents, particularly the Saudia L1011 which resulted in 301 fire fatalities, more emphasis is now being placed within the FAA's Cabin Fire Safety Program on in-flight fire problems.

It is generally agreed that ignition of jet fuel represents the greatest potential danger in aircraft crash accidents. No other conclusion seems possible when one considers that jet fuel is extremely flammable and is carried in large quantities in modern jet transports; e.g., the fuel tanks capacity of an L1011 is 23,000 gallons (reference 3). In accidents where large quantities of fuel are released and ignited, and where the integrity of the fuselage is damaged to a degree that enables major portions of the cabin to be directly subjected to the fuel fire, the dominance of the fuel fire is clear. However, accidents do occur with relatively small quantities of fuel spillage, or none at all, and with the fuselage primarily intact, that result in a cabin fire leading to fire fatalities. These accidents are part of a classification of accidents defined as survivable; i.e., those accidents in which one or more of the occupants survive the impact. In an FAA study for the period 1964 to 1974, it was estimated that 39 percent of the fatalities were attributable to fire in survivable accidents (reference 4).

It is difficult, if not impossible, to assess the role of a particular interior material, or materials, in general, on the number of fatalities in crash accidents accompanied by fire. Numerous factors are known to affect the behavior of a material in a fire (reference 5), while the present status of fire technology does not allow for the prediction of the combined effect of each factor on the overall threat to cabin occupants under a given fire condition. Nevertheless, there does exist both direct and indirect data of the importance of interior materials on survivability during a postcrash cabin fire. Of a direct nature, is the measurement of high levels of blood cyanide in some accident victims (reference 6). These measurements have been incorporated into U.S. accident investigations since 1970. However, the relationship between cyanide levels in blood samples taken from accident victims to the concentration of cyanide to which the victim was exposed to during the fire has been questioned (reference 7). Another form of direct data is the fact that although most crash accidents are accompanied by fuel spillage, several fatal accidents have occurred with insignificant or no fuel release. For example, at Salt Lake City in 1965, a 727 crashed and caught on fire as the result of a severed fuel line beneath the cabin floor. The initial fire consisting of a relatively small quantity of spilled fuel was probably not life threatening in itself, but was of sufficient intensity to ignite the cabin interior, which resulted in 43 fatalities (reference 8). More recently, a 747 crashed in Seoul, Korea, in 1980, without any fuel spillage, yet the ensuing fire killed 15 people. More of an indirect nature of data is the recognition that an aircraft cabin is an enclosure with limited egress, high loading of plastic and synthetic interior materials, and high occupancy density. Past large-scale tests conducted in the United States on simulated cabin interiors or mockups (references 9, 10, and 11) have demonstrated that hazardous and fatal conditions will arise from ignition of interior materials with the development of a self-sustaining fire. In the laboratory, a wide range of heat, smoke, and toxic gas levels have been measured during testing of in-service materials subjected to intense fire exposure (reference 12). These test data gathered under specific and, perhaps, not completely realistic conditions indicate the potential dangers of burning interior materials.

Complexity of cabin design is one of the many factors that make it difficult to determine the importance of interior materials on postcrash cabin fire survivability. The cabin interior is completely lined with multi-layered materials and furnished with hundreds of seats. Each component is selected with due consideration given to fire safety, functionality, durability, processability, cleanability, economics, and, of increasing importance, weight. Current FAA regulations specify that all major components "self-extinguish" after a prescribed exposure to a small flame (reference 13). Moreover, at their own initiative, the airframe manufacturers strive to select materials with low-smoke emissions and low-flame spread rate. One manufacturer also screens materials for emission of specified toxic gases. Despite apparent differences in design goals and philosophy, the cabin materials used by the three major U.S. airframe manufacturers are very similar. The composite panels which constitute the bulk of the sidewalls, stowage bins, ceilings and partitions are basically composed of a Nomex™ (aramid) honeycomb core with fiber glass facings impregnated with epoxy or phenolic resin and a decorative laminate composed of Tedlar™ (polyvinyl flouride) layers or Tedlar and polyvinyl chloride layers. A greater variety of materials are used for floor coverings and seat cushions, which are selected by the airlines, but are typically wool pile carpet and cushioning composed of flame retardant (FR) urethane with a wool (90 percent)/nylon (10 percent) upholstery cover. A full-scale test configuration should include, at least, the major cabin usage categories; i.e.,carpet, seats, sidewall panels, stowage bins, and ceiling panels.

From a practical necessity, aircraft materials are and should be selected based on the results of small-scale fire tests. However, it is generally recognized that small-scale test results do not reflect the behavior of a material in its end-use application under realistic fire conditions. Therefore, until more realistic and meaningful small-scale tests are developed, the FAA, as well as many other organizations engaged in fire testing, is relying more heavily on large-scale tests and, to a much lesser degree, full-scale tests for materials evaluation. Full-scale tests are usually performed for more far-reaching reasons; namely, define the nature of a perceived fire problem, identify governing parameters, bracket fire conditions, examine the relevency of small-scale test results, and demonstrate the benefit of improved material or fire management systems.

In the past, the number of fire tests consisting of exposure of a realistically-furnished cabin test article to a fuel fire have been small in number (reference 9, 11, and 14). Each of these test programs were deficient in one or more of the following manners:

(1) Instrumentation was incomplete or improper (e.g., absence of smoke measurements or test animals, improper sampling of reactive acid gases);

(2) The test article was not fully protected to allow for multiple tests, causing the results to be inconclusive or unconvincing;

(3) The fuel fire was unrealistic in terms of size (too small) and position (placement was inside the fuselage). The effect was to exaggerate the contribution of fuel-fire smoke to the cabin environment and to subject the interior materials to unrepresentative low levels of radiant heat;

(4) Precautions taken to negate the effect of random ambient wind, which has a pronounced and, sometimes, dominant effect on external fuel fire penetration through a fuselage opening (references 15, 16, and 17), were ineffective. Therefore, the effect of the fuel fire with regard to heat exposure of the interior and its contribution to cabin hazard levels was not identical from test to test; and

(5) Protection of the test article interior with sheet metal probably created higher wall heat loses than would have been encountered with a real interior. Thus, the wall loses could have far exceeded the levels measured in enclosure fires; i.e., 50-95 percent of the total energy released by the fire (reference 18). None of the test articles simulated a wide-body cabin. In the development of the cabin fire test article described subsequently in this paper, an attempt has been made to rectify the problems, enumerated above, that were encountered by earlier investigators.

The FAA convened the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee to "examine the factors effecting the ability of aircraft cabin occupants to survive in the postcrash environment and the range of solutions available" (reference 19). The committee approved the objectives set forth by FAA in its program plan (reference 1) for full-scale cabin fire testing. After examination of the contemporary makeup of aircraft cabin interiors, the committee concluded that a near term solution was available to protect or replace the FR urethane used in seat cushions, which was believed to be the most flammable of all the interior materials used is large quantities. The second part of this paper describes the evaluation of seat cushion blocking layers and improved foam cushions under large- and full-scale test conditions.

Although the potential flammability of flexible urethane foam has been recognized for 10 years (reference 10), it has only been until the last several years that more fire-safe and practical alternates have emerged. While neoprene foam has always possessed excellent flame resistance, earlier formulations were extremely smokey and heavy. The development of LS-200 represented a marked improvement in neoprene technology, by reducing smoke emissions and weight and improving physical properties (reference 20). Nevertheless, the reduction of neoprene foam density to the 7-8 pounds per cubic feet range was still prohibitively high for the aviation market. In order to retain the cushion properties of urethane without the weight penalty of a full neoprene cushion, the concept of a fire blocking layer encasement was developed.

By design, the blocking layer encasement inhibits or prevents the fire involvement of the flammable urethane foam underneath. A commercial foam fire blocking layer was developed in the mid 1970's and given the trade name Vonar™. Extensively evaluated by FAA and others, Vonar is a thin neoprene foam layer that is heavily treated with flame retardants (approximately 40 percent by weight). A number of mechanisms contribute to its fire blocking behavior, but, most important, is the formation of a stabile and strong char when it is exposed to heat or flame. The insulative properties of the char, of course, significantly reduce the rate of heat transfer to the urethane foam sublayer. Although Vonar had been demonstrated to be highly effective against moderate ignition sources, such as newspaper or wastebasket fires (reference 21), or fires likely to occur in rapid transit vehicles (reference 22), the FAA test program was the first to realistically subject the material to the intense radiant heat produced by a large fuel fire.

DISCUSSION

DESIGN OF FULL-SCALE TEST ARTICLE

The survivable postcrash fire scenario selected for study consisted of an intact fuselage with open doors, as might exist during evacuation, and an external fuel fire adjacent to an opening. Selection of the scenario was based on creating a realistic postcrash condition with an external fuel fire rather than a fuel fire within the cabin which is an easier test to perform but is less realistic. Moreover, it was believed that placement of the fire outside the fuselage would more properly balance the cabin hazards from the fuel fire and burning interior materials. Another important aspect, as discussed later, was to develop a test fire that would recreate the intense radiant heat produced by a large fuel spill fire. An accident occurred after the fire scenario was conceived which was a near duplicate, attesting to the realism of the scenario (reference 23).

The full-scale test article was a modified surplus C-133 aircraft. The important dimensions and overall layout are shown in figure 1. The cross sectional area is simular to, although slightly smaller than, a wide-body jet cabin. An interior volume of 13,200 ft^3 is representative of a wide-body jet. Reference 15 describes in detail the test article design.

The test article was designed for fire durability to allow for the conduct of numerous tests. This was accomplished by stripping the interior of all combustibles, lining the inside surfaces with non-combustible ceramic and fiber glass materials, and installing a CO_2 total-flooding, fire protection system. It was believed that the ceramic/fiber glass materials provided for more realistic wall heat transfer than sheet metal. The test article has withstood approximately 150 tests, although on several occasions extensive repairs had to be made.

The opening adjacent to the fire was a wide body type A door opening. However, the opening was treated as a rupture rather than a door; i.e., seats are placed in the opening. This size opening was selected because descriptive information on fuselage rupture size from actual accidents was found to be lacking.

A full-scale fire test facility houses the test article. A specially designed ceiling allows for the setting of large fuel fires inside the test bay. The facility provides an environment that is basically isolated from fluctuating ambient winds, which can destroy test repeatability and make test results analysis very difficult, and allows for testing throughout the year under all weather conditions. A large fan can simulate a range of wind speeds at the fire door, providing the flexibility of varying, as desired, the degree of fuel-fire flame penetration into the cabin. Figure 2 is a photograph of a typical fire test with the facility shown in the inset.

The C-133 test article is extensively instrumented to measure the major hazards produced by a cabin fire at various cabin locations as a function of time. The most extensive measurement is that of air temperature; a series of thermocouple poles on the fuselage centerline are located throughout the cabin. Gardon gage-type calorimeters, primarily clustered around the fire door, measure the radiant and convective heat flux from the jet fuel fire and ensuring cabin fire. Smoke density is measured by light transmissometers, consisting essentially of a light source and photoelectric cell receiver. Gas concentrations are measured by continuous analyzers and from post-test analysis of batch samples taken at regular intervals during the test. The gases analyzed continuously at four cabin locations include carbon dioxide (CO_2), carbon monoxide (CO) and oxygen (O_2). The remaining gases analyzed from batch samples consist of two classes: acid gases (e.g., hydrogen fluoride (HF), hydrogen chloride (HCl), etc.) and organic gases (e.g., hydrogen cyanide (HCN), etc). The acid gases, particularly HF and HCl, are analyzed by ion chromatography of samples collected in small tubes filled with glass beads that are coated with a sodium carbonate solution. The organic gases, particularly HCN, are analyzed by gas chromatography of samples collected on Tenax™ tubes. A detailed description of the analytical methodology for the acid and organic gases is contained in reference 24. Exclusive of the gases analyzed from batch samples, the cabin hazard measurements are recorded on a computer data acquisition system, and converted into engineering units and plotted after completion of a test. Cabin fire growth is monitored during a test by video coverage. Color photography documentation includes 35mm sequential photographs at 5-second intervals, and 16mm movies.

DERIVATION OF FUEL FIRE TEST CONDITIONS

Since the quantities of jet fuel potentially involved in a postcrash fire are enormous, the realism of past full-scale fire tests utilizing small amounts of fuel was questionable. An important design goal for the C-133 test article was to derive a test fuel fire of intensity representative of a large fuel fire. Past studies of the burning behavior of pool fires indicated the dominance of thermal radiation, as compared to convection, for pool fires above 3 feet in diameter, radiation was relatively invariant at approximately 14 British Thermal Units per square foot per second (Btu/ft^2-sec) (reference 25). Of concern, however, was the amount of radiation into a cabin interior from a large fuel fire adjacent to a type A door opening. Therefore, a study was performed using models of the C-133 test article of various diameters, subjected to a fuel fire of width equal or greater to the model diameter (reference 26). The study was performed indoors to eliminate wind as a factor. It was determined that the radiant heat flux on the fuselage symmetry plane at the fire door station at an elevation of one half the door height was 1.8 Btu/ft^2-sec for an infinite fire and zero wind conditions. In addition to establishing a design goal for the C-133 test fire, the model tests in conjunction with a mathematical analysis of the radiant field inside the fuselage, demonstrated the presence of severe radiant heat gradients within the fuselage enclosure (reference 26). Thus, it became evident that, during its initial stages, an interior fire would be highly localized, and that at relatively small distances away from the fire the radiant heat flux would be virtually zero.

In order to validate the aforementioned modeling results, a surplus DC-7 aircraft with a fuselage opening scaled to the C-133 opening was subjected to a 30-foot-square pool fire (reference 16). Figure 3 contains a comparison of the symmetry plane heat flux measured during three tests with the modeling value of 1.8 Btu/ft^2-sec. As shown, a reasonable agreement was achieved between the two tests performed under calm wind conditions and the modeling prediction for zero wind. With a wind fluctuating from 4-10 miles per hour (mph), the measured radiant heat flux undulated above the modeling prediction because of the intermittent penetration of flames into the cabin caused by the winds. The increase in radiation is due both to the larger flame surface emitting heat and the smaller distance between the flame surface and measuring calorimeter.

In the C-133 test article, the fuel pan was located at the bottom edge of the opening, rather than on the ground, in order to best assure that a solid flame surface would cover the entire opening, as would result from a large ground fire. Initial tests with a 4-foot-square pan, which was slightly wider than the opening, proved that this pan size was inadequate due to incomplete flame coverage over the opening, resulting from "necking" of the fuel fire. Subsequent tests were performed with progressively larger pan sizes, and adequacy of the pan size was rated in terms of the completeness of flame coverage over the opening and closeness of the cabin symmetry plane radiation to the modeling prediction for an infinite fire. A pan that was 8 feet wide and 10 feet long completely covered the opening with flames and produced a symmetry plane heat flux of 1.5 Btu/ft^2-sec (reference 15). Although this pan size produced radiation at the symmetry plane which was slightly less than the level expected from an infinite fuel fire, it was obviously representative of a large fuel fire and was thus selected for the "standard" C-133 fuel fire. Moreover, it was feared that a larger fuel fire might jeopardize the safety of the facility housing the test article or, perhaps, cause the early destruction of the test article itself. In a typical fire test, 50 gallons of fuel are placed in the fuel pan atop a water base to assure uniform fuel depth throughout the pan. This fuel quantity assures an unwavering fire for at least 4-1/2 minutes, which is the usual test duration (reference 15).

A protective covering of steel sheeting over a fibrous ceramic matting prevents melting of the C-133 aluminum fuselage skin adjacent to the fuel fire. This protective measure, which provides an opening of unchanging area for fuel fire penetration into the interior, does not detract from the realism of the test article. During an actual wide-body accident, a major fuel fire burned for an estimated 2 - 3 minutes, before extinguishment, without fuel fire penetration into the cabin (reference 23). Therefore, for a wide-body aircraft exposed to a major fuel fire for 3 - 4 minutes, it is likely that the fuel fire hazards passing through an initial opening will far exceed the increase in hazards as the opening enlarges.

CABIN HAZARDS CREATED BY THE FUEL FIRE

In order to understand the role of interior materials in a cabin fire arising from an external fuel fire, it is necessary to first examine the effects of the fuel fire alone. This was accomplished by setting a large series of fuel-fire tests with the C-133 interior completely devoid of interior materials (reference 15). The tests were performed outdoors with the test article configuration shown in figure 1 and the primary variables were ambient wind velocity (uncontrolled) and fuel-fire size. In order to examine the wind conditions of interest, which were winds of a relatively low speed (0 - 5 mph) and in a direction to cause flame penetration into the interior, tests were run in the early morning when weather conditions were favorable.

Wind conditions were found to have a dominant effect on the rate of hazard development inside the cabin. This conclusion was also reached in related studies where the effect of door opening locations away from the fire, relative to the wind direction, were also found to be an important factor (references 16 and 17). The effect of wind speed on cabin temperature is shown in figure 4 when the C-133 test article was subjected to an 8- by 10-foot fire upwind of the fuselage. Except for the low wind test (1.5 mph), the trend for the most part was to have higher cabin temperatures as the wind speed increased. The principle implications of this finding are twofold: (1) for a specific aircraft/fuel-spill crash configuration, the cabin hazards caused by burning fuel vis-a-vis burning interior materials are highly dependent on ambient wind and cabin draft conditions; and (2) for the C-133 test configuration, the degree of fuel flame penetration into the cabin, and the resultant fire exposure of interior materials near the fire opening, can be adjusted over a wide range of values by utilizing an artificial wind (fan). The small increase in cabin temperature shown in figure 4 under zero wind is the result of a significant portion of the fuel fire products, entering the cabin, becoming entrained back into the fire. The insignificant temperature rise for the zero wind case is also indicative of the results when the fuel fire is downstream of the fuselage (references 15 and 16); i.e., minimal cabin hazard accumulation even though the radiation into the cabin is intense.

The relationship between convective heating (and smoke and gas accumulation) within the cabin and radiative heating for a given wind speed was found to be dependent on fuel-fire size (reference 15). Because flame bending increases with decreasing fire size for a given wind speed, a small fire size (e.g., 4- by 6-feet) will create greater heat and smoke accumulation inside the cabin but less radiative heating than a larger fire size (e.g., 8- by 10 feet). Beginning with this experimental finding, the subsequent discussion is an analysis of the possible ramifications of the utilization of small fuel pan fires in full-scale tests. Since the amount of heat and smoke produced by interior materials increases with the level of radiation, rather than of convection inside the cabin, the proportion of heat and smoke accumulation inside the cabin from burning fuel vis-a-vis burning interior materials is greater for smaller fuel fires. Thus, the use of unrealistically small fuel fires for test purposes because of their ease of handling may produce misleading results. A small fuel fire will create higher cabin hazards from the fuel fire than might exist from larger fires, but will not cause the interior materials to burn as extensively as might a larger fire.

Tests performed with the C-133 test article devoid of interior materials indicated the prominence of certain cabin hazards over others when the fuel fire is the dominant threat. In tests with significant flame penetration into the cabin, elevated temperature exceeded human tolerance limits and smoke obscured visibility; however, CO concentrations were extremely low and clearly nonhazardous. Since high levels of carboxyhemoglobin are often measured in blood samples taken from aircraft fire victims (reference 6), in light of the C-133 test results, and without consideration of other scenarios, it appears as if this finding cannot be explained in terms of a dominant fuel fire. The source of high levels of carboxyhemoglobin in some fire accident victims may have been CO produced by burning interior materials.

CABIN HAZARDS CREATED BY BURNING INTERIOR MATERIALS

In order to study and measure the full-scale hazards of cabin interior materials subjected to an external fuel fire, a section of the C-133 test article, centered at the opening adjacent to the fuel pan, was lined and furnished with wide-body type materials. Samples of the various materials were tested and determined to be, as required, compliant with FAA flammability regulations prescribed in Federal Aviation Regulation (FAR) 25.853 (reference 13). As shown in the cutaway isometric drawing in figure 5, the materials were arranged in a realistic fashion. The following summarizes the materials' loading: (1) 12 flat, honeycomb composite panels, each 4 by 6 feet, comprised a 24-foot-long drop ceiling; (2) 6 lengths of honeycomb composite overhead stowage bins were mounted on both sides of the cabin; (3) 8 contoured honeycomb composite sidewall panels with window reveals, each 3.3 by 5.5 feet, were fastened to the insulated inner fuselage; (4) a total of 21 seats, including 6 doubles and 3 triples, composed of wool (90 percent)/nylon (10 percent) upholstery covers and FR urethane cushions, were arranged into 3 rows to form a dual aisle interior; and (5) a wool (100 percent) pile carpet was placed over the aluminum-faced cabin floor. The ceiling panels and carpet were new, while the sidewall panels, stowage bins, and seats were obtained from refurbished wide-body aircraft.

The materials were subjected to a zero wind fuel fire. This condition was selected because the cabin hazards solely arising from the fuel fire would be minimal and clearly survivable as shown in previous test (see figure 4). In this manner, the cabin hazards with materials installed in the test article would be unmistakably produced by the burning materials and not by the fuel fire.

A revealing account of the fire growth inside the cabin was obtained from the color photographic coverage, including 35mm motorized stills and 16mm movies. Examination of these films demonstrated that for approximately 2 minutes, the cabin fire was limited to the area in the immediate vicinity of the fuselage opening adjacent to the fuel fire. The outboard double seat at the fire opening was almost completely engulfed in flames, as was the back of the outboard seat forward of the opening and the front of the seat behind. Fire had not progressed to the triple seats comprising the center section, although some smouldering was evident. Also in evidence was intermittent flashing in the smoke layer under the ceiling by the opening. Although the heavy smoke obscured the upper cabin, the high temperatures recorded in this area and the existence of flashes indicated that ceiling and stowage bins near the opening were pyrolyzing and, perhaps, burning. At approximately 2 minutes, within a matter of 10 seconds, or less, the remaining interior materials were suddenly set aflame or underwent pyrolysis. This event has been observed in many types of enclosure fire tests and has been given the name "flashover." Photographs taken at 5-seconds intervals shown in figure 6, illustrate the suddeness and totality of the flashover.

The major hazards produced by the cabin fire, aft of the galley partition, are shown plotted as a function of time in figure 7. The survivability is of interest in this section of the cabin because (1) the evacuation process is usually in a direction away from the fire origin and (2) in some past accidents victims have been found clustered near exits.

The occurrence of flashover indicates that conditions throughout the cabin will become nonsurvivable within a matter of seconds. Of concern, thus, is whether any of the preflashover hazards were at a level to impair or prevent escape. An examination of figure 7 indicates that the acid gases HF and HCl accumulated in the aft cabin at least 1 minute before any of the remaining hazards. These gases were produced by the burning honeycomb composite panels which comprise the ceiling, stowage bins, and hatrack. The somewhat similar shape of the curves is a clue that the two gases emanated from the same source. Moreover, a past study of thermal degradation products from aircraft materials indicated that HF and HCl, the latter in higher yields, are produced by some panels (reference 27). The source of HF was the 3-Mil Tedlar polyvinylfluoride decorative film which covers the panels. The source of HCl is probably the flame retardants used in the epoxy resin which impregnates the fiber glass facings and adheres the panel components together. Another source of HCl was the polyvinylchloride (PVC) seat components (armrest covers, side panels) and those components containing chlorinated fire retardants (cushions). It appears as if the initial gas peak was caused by the rapid thermal degradation of the decorative film and fiber glass facing resulting from the intense radiant heat from the fuel fire at the beginning of the test. The second gas peak was caused by the rapid fire involvement associated with flashover of all the interior materials. The early concentrations of acid gases (e.g., 300 parts per million (ppm) and 140 ppm for HCl and HF, respectively, at 60 seconds) are considered to be significant levels. Composite panel lining materials — the source of these gases — are important potential contributors to cabin fire hazards because of their large surface area and, in many cases, vulnerable location in the upper cabin area.

Elevated temperature, smoke, and HCN were the remaining hazards detected before the onset of flashover. Flaming conditions during a postcrash cabin fire, as opposed to a smouldering fire, make the presence of high temperatures to be expected. More unexpected was the low concentration of HCN, considering that wool is used for seat upholstery and carpet, and that wool produces high yields of HCN, approximately 40 milligrams per gram (mg/g), when pyrolyzed oxidatively (reference 27). A number of explanations for the low HCN concentrations are plausible, including (1) burning of the HCN during flashover, (2) because of the prominence of flaming, production of nitrogen oxides by the wool rather than HCN (reference 28), or (3) insufficient fire involvement of the wool due to relatively low loading and to location in the lower cabin. An interesting result was the late detection of smoke at approximately 100 seconds, in contrast to HF and HCl which were detected much earlier into the test.

In order to assess the relative importance of each cabin fire hazard, a hypothetical human survival model was formulated. (The structure of the model was suggested by Dr. Charles Crane at the FAA's Civil Aeromedical Institute. The authors are grateful for his important contribution to this paper.) The model computes incapacitation in a fire environment composed of a number of toxic gases and elevated temperature, each varying with time. The major assumptions were twofold: (1) the hazards are additive and (2) for the toxic gases, the classical hyperbolic relationship exists between gas concentration and time of incapacitation. Thus, based on the latter assumption, for a gas species i

$$c_i T_i = K_i$$

and

$$FED_i = \int_0^t c_i \, dt$$

where

c_i = concentration of gas species i
T_i = time-of-incapacitation
K_i = incapacitation dose of gas species i, a constant
FED_i = fractional effective dose, or the ratio of the actual dose due to gas species i to the incapacitation dose
t = time

The incapacitation dose constants, K_i, were calculated from the best available data in the literature (reference 28), and are tabulated below:

Gas Species i	K_i (ppm - minutes)
CO	24,000
CO_2	750,000
HCN	480
HF	1,140
HCl	2,400

The table reflects the relative toxicity of the gas species of interest; e.g., HCN is five times as toxic as HCl.

The effect of elevated temperature on incapacitation was taken into account by utilizing the empirically based curve fit, derived by Crane (reference 30), shown below

$$t_c = Q_o/T^{3.61}$$

where

t_c = time to thermal collapse (incapacitation), minutes
T = air temperature, degrees centigrade
Q_o = 4.1×10^8 a statistically derived proportionality constant

The above relationship is based on data from human exposure to a constant temperature. In order to apply this relationship to the more common time-dependent fire environment, the thermal history curve was divided into 1-second intervals. By considering Q_o as a heat factor related to the caloric intake that a body must absorb to produce thermal collapse, the thermal fractional effective dose, FED_T, becomes

$$FED_T = \frac{\Delta t \sum T^{3.61}}{Q_o}$$

Therefore, assuming the hazards to be additive, the fractional effective dose for the mixture, FED, becomes

$$FED = FED_T + \sum FED_i = \frac{\Delta t \sum T^{3.61}}{Q_o} + \sum \frac{\int_0^t C_i dt}{K_i}$$

The hypothetical time-of-incapacitation for the mixture is the time at which FED = 1.0.

The survival model described above is hypothetical. Its main purpose is to provide a means of predicting the time-of-incapacitation within a fire enclosure, based on measurements of elevated temperature and toxic gases concentrations which change, in some cases substantially, with time. Thus, it is a tool for reducing a fairly large number of somewhat abstract measurements into a single, cogent parameter: time-of-incapacitation, or the hypothetical time at which an individual can no longer escape from a fire environment. How well the model relates to actual escape potential is unknown and, realistically, cannot be determined. It is known that segments of the model are deficient for lack of available information. For example, no data exists on the effect of irritant gases (e.g., HCL, HF) on acute human escape potential. (FAA has sponsored new research at Southwest Research Institute to determine "the threshold concentration for escape impairment by irritant gases (HCL and acrolein, initially) using a nonhuman primate model and a relevant behavioral task that can be extrapolated to man.") Thus, the HCl and HF incapacitation doses utilized in the model are simply based upon extrapolation from threshold limit values (TLV's) for an 8-hour work environment. Confidence in the model is greater for the prediction of the relative escape time between tests on different material systems than on the prediction of absolute escape times.

The human survival model was applied to predict the survivability in the aft cabin based on the hazard measurements taken at the location plotted in figure 7. As shown in figure 8, the hypothetical survival time was 159 seconds when wide-body materials were installed in the cabin. Conversely, when no materials were installed in the cabin, corresponding to an idealistic and unrealistic completely noncombustible interior, there was no detectable loss in survivability, i.e., FED = 0 throughout the test. The slope of the survival curve with wide-body materials installed in the cabin increased drastically shortly after the flashover because of the rapid increase in hazards caused by the flashover. Until this test time, the survival curve was entirely driven by HF and HCl. As discussed earlier, the incapacitation doses of these irritant gases are unknown and the values used in the survival model are calculated estimates. If one ignores the hazards of HF and HCl, the survival curve becomes driven primarily by temperature and, to a lesser degree, CO. Also, the fractional effective dose will not increase above zero until 135 seconds, and will exhibit a much steeper slope than when the irritant gases are included. Four of the six hazards considered in the model eventually exceeded their incapacitation dose, as follows: temperature at 180 seconds, HF at 210 seconds, CO at 237 seconds, and HCl at 248 seconds. The fractional effective doses of the remaining hazards, CO_2 and HCN, were comparatively insignificant (0.2 and 0.04 at 240 seconds, respectively).

It has long been recognized that a margin of safety exists near the floor inside an enclosure fire. The wisdom of this advice was examined by measuring the major hazards at three elevations at test station 650 and calculating the survival time at each elevation. These survival curves are plotted in figure 9(a) and verify that survivability is possible for a longer period, the closer one is to the floor. A 34-second improvement was calculated between 5 feet 6 inches and 3 feet 6 inches, but the improvement was only 9 seconds between 3 feet 6 inches and 1 foot 6 inches. In figure 9(b) the relative importance of each hazard at the calculated survival time is graphed. The irritant gases HF and HCl again drove the survivability calculation at all three elevations. Although a contributing factor at 5 feet 6 inches, heat (elevated temperature) became negligible at the two lower elevations. Instead, CO was found to be a more important factor although this is not adequately shown in figure 9(b). This is more apparent when the survivability calculation is extended beyond the survival time; within several minutes CO will become the dominant hazard at the two lower elevations. Thus, if it is assumed that the HCl and HF incapacitation doses utilized in the model are low, and, if they are raised (i.e., the incapacitating effect of these irritant gases is made less potent in the model), then CO will be the dominant factor affecting incapacitation. Also, since CO is a more lethal agent than either HF or HCl, it may be argued that CO would be primarily responsible for any fatalaties caused by inhalation of gases near the floor. It may also then be argued that a plausible scenario for demise of an individual during a cabin fire is incapacitation, while standing, from exposure to irritant gases and heat, and, after collapsing to the floor, death from CO asphyxiation.

The most striking feature of a cabin fire is the smoke layer which because of buoyancy appears to cling to the ceiling. Figure 10 is a graph of the vertical temperature profile at various test times at test station 270, which was the first thermocouple pole station aft of the last seat row. The inflection point in the temperature profile defines the smoke layer thickness. Figure 10 illustrates that the cabin environment may be approximately described by two zones — a hot zone at the ceiling, which thickens as the fire progresses, with a linear temperature profile, and a much cooler zone in the lower cabin with a uniform, but above ambient, temperature. The temperature differential between the ceiling and lower cabin was very large; e.g., at 2-1/2 minutes the differential was higher than 1000° F. This finding has a bearing on the relevance of small-scale tests (ceiling materials are exposed to higher convective heat fluxes than are carpets, for instance).

The existence of a hot zone also has a bearing on evacuation. For example, at a station only 12 feet aft of the fire (figure 10), conditions would be clearly survivable from convective thermal exposure, as late as 2 minutes (10 to 15 seconds before flashover), for an individual who crouches in order to avoid exposure to the hot smoke layer. Moreover, a hot, smoky layer can nullify the benefit of ceiling-mounted emergency lighting, possibly by causing thermal failure in the units, or by obscuring exit signs or blocking illumination.

The existence of large heat losses into the walls of an enclosure during a fire and the entrainment of lower zone cool air into the hot smoke layer creates corresponding losses in the heat content, or temperature, of the smoke layer gases as they are transported away from the fire origin. Figure 11 is a graph of the symmetry plane air temperature at the ceiling throughout the cabin at various times into the test. Because of the aforementioned heat losses, the ceiling temperature decreased significantly with distance away from the fire. Although measurements near the fire were off-scale at 1800° F after 2-1/2 to 3 minutes into the test, because the thermocouples were not shielded from radiation these readings may be higher than the actual air temperature. The temperature profile at 2 minutes indicates that a large area of the ceiling was subjected to temperatures in excess of the thermal decomposition temperature of the composite panels, approximately 200 to 350 degrees centigrade (°C), before the occurrence of flashover (reference 31). Examination of figure 11 illustrates that the galley partition tended to confine much of the heat to the cabin section forward of the partition. A related observation has been made in accident aircraft where fire damage was more extensive on the fire origin side of a class divider than on the protected side. It is of interest to note that the ceiling temperature aft of the galley partition is more uniform than the ceiling temperature in the forward cabin. This apparent uniformity may have resulted from more active mixing in the smoke layer caused by the partition openings and by entrainment of fresh air through the exhaust door.

EVALUATION OF SEAT CUSHION FIRE BLOCKING LAYERS

The C-133 test article was utilized to evaluate the effectiveness of aircraft seat cushion fire-blocking layer materials. This work was undertaken in response to the SAFER Advisory Committee recommendation pertaining to cushioning fire blocking layers (reference 19). Because of the high work priority, general interest in these materials and lack of data under postcrash fire exposure, the evaluation was performed under both large- and full-scale conditions to assure highest confidence in the test results.

This paper will be limited to the initial work on foam blocking layers (Vonar and LS-200) to demonstrate the effectiveness of the concept. More recently, aluminized fabrics such as Preox™ and Norfab™ have exhibited promising fireblocking characteristics at less weight than the foams. Both blocking layer systems will be discussed in a separate comprehensive final report.

The fire blocking layer materials were evaluated at a number of seating configurations and test conditions, each with a specific objective. The bulk of the tests were performed on single or multiple seats exposed to the fuel fire at the fuselage opening without any other interior materials installed in the cabin. The first series of tests were on double seat cushions supported by a metal frame. In this manner, performance benefits provided by blocking layers could be determined without contributions and possible confusion from the fire involvement of other materials. Subsequent tests were performed on real seats to examine the benefit in the context of remaining seating materials. Multiple seats were evaluated to study the effect of blocking layers on seat-to-seat fire growth. In order to examine the effect of the primary test configuration (76-inch by 42-inch opening, seat adjacent to opening), a series of tests were run with a smaller opening (2-foot square), and another series treating the opening as a doorway (with appropriate rearrangement of seating). Finally, tests were performed with a section of the cabin completely installed with interior materials in order to determine fire-blocking layer benefits under the most realistic conditions achievable.

The forward cabin temperature history is plotted in figure 12 for the initial test series on cushioning mounted on a double seat, metal frame. In this test, as throughout the program, the seat upholstery fabric was a wool (90 percent)/nylon (10 percent) blend. The results were very encouraging in that each concept exhibited a significant improvement over the baseline cushion, FR urethane. Two Vonar types, each 3/16-inch thick, were evaluated — polyester (PE) scrim and fiber glass (FG) scrim. Both Vonar materials produced results similar to the LS-200 full cushion, which is considered to be the premium flexible foam cushion in terms of fire safety. The Vonar results were considerably better than the results with LS-200 as a blocking layer (at double the thickness of Vonar). The superiority in fire performance of seat cushions protected with Vonar, as compared to unprotected cushions, was consistently demonstrated throughout the program for each of the aforementioned series of tests.

What is the safety benefit of seat cushion fire blocking layers during a postcrash cabin fire within the context of the remaining interior materials? This question was answered by performing a test with a section of the C-133 test article completely lined and furnished with interior materials (see figure 5), and with the FR urethane cushions encased in Vonar PE blocking layers. The difference in survivability between the full-scale test with Vonar and the full-scale test with unprotected cushions was the safety benefit. Figure 13 is a graph of the calculated fractional effective dose history for each of these tests. The calculation does not include the effect of HCl in any of the tests because of a malfunction in the analysis of HCl in the test with Vonar. The calculated safety benefit provided by Vonar was 60 seconds for the particular fire scenario that was simulated. In order to compare the performance of Vonar protected cushions with the ultimate protection — noncombustible cushions — a full-scale test was conducted with the seat upholstery covers stuffed with Kaowool™, a ceramic fibrous insulation. Surprisingly, the increase in safety provided by the noncombustible cushions over that provided by the Vonar protected cushions was only 8 seconds. This comparison indicated that the fire protection offered by Vonar was nearly equivalent to a noncombustible cushion. Thus, if not a practical solution in itself, Vonar, by its excellent performance in full-scale fire tests, provided a lofty and achievable fire performance goal for seat cushion blocking layer materials under consideration for aircraft usage. Figure 13 also indicates that, in the test conducted with a noncombustible interior, there was no detectable detriment to survival. Thus, major potential improvements in cabin fire safety may exist, beyond that provided by seat cushion blocking layers, from an upgrading of the fire performance of the remainder of the cabin interior (e.g., ceiling panels, stowage bins, etc.). Whether there exists materials with enhanced fire performance, as well as acceptable functionality, durability, processability and weight, remains to be determined.

Smoke was not a component of the human survival model discussed previously in this paper. Aside from possible physiological and psychological effects which are presently beyond mathematical description, the major impact of smoke is to obscure visibility and, thereby, increase the time required to evacuate an airplane. Thus, the net effect from the existence of dense smoke will be prolonged exposure of cabin occupants to fire hazards, which may ultimately cause incapacitation of some occupants before they are able to escape. The loss in visibility in the aft cabin was calculated and plotted in figure 14 for the previously discussed full-scale tests. The following simple equation derived by Jin (reference 32) was employed to compute visibility from the light transmissivity measurements:

$$D/L \times V = 3.5$$

where

D = optical density ($D = \log \frac{1}{T}$, T is fraction of light transmitted)

L = light transmissometer path length

V = visibility of a backlighted sign

The most striking feature of the curves in figure 14 is the rapidity by which visibility became obscured; e.g., in some cases visibility was reduced from the length of the cabin to less than the width of the cabin in approximately 15 seconds. Also, by comparing figures 13 and 14, it is apparent that smoke became an important factor well before survival was no longer theoretically possible. For example, visibility was reduced to less than the width of the test article at 30 to 60 seconds before the hypothetical survival time for each of the three full-scale tests with interior materials. The ranking of results for visibility (figure 14) was identical to the rankings for hypothetical survival time (figure 13), although the time increments between the curves were not equal. For example, the application of Vonar to aircraft seats increased the hypothetical survival time by 60 seconds (figure 13), whereas the improvement in visibility from reduced smoke levels was 48 seconds (when visibility was reduced to the cabin width).

SUMMARY OF SIGNIFICANT FINDINGS

Based on the full-scale tests and analysis described in this paper, which examined the cabin fire hazards arising from an external fuel adjacent to a large fuselage opening in an intact fuselage, with minimal fuel-fire flame penetration but intense radiation into the cabin, the following are the significant findings:

(1) Burning cabin interior materials can be the primary factor affecting occupant survivability in certain types of postcrash fires despite the presence of a large fuel fire.

(2) Uncontrolled postcrash fires in an intact fuselage will produce a flashover condition, which will be followed by a loss in survivability throughout the cabin.

(3) The only fire hazards of significance measured before the onset of flashover were the irritant gases, HF and HCl, and smoke produced by burning composite panels and, possibly, seats.

(4) In tests with zero wind and the cabin interior realistically furnished and lined with interior materials, application of a Vonar fire-blocking layer on seat cushions improved the calculated survival time in the aft cabin by 60 seconds.

(5) Potential benefits to cabin fire safety beyond those provided by seat cushion blocking layers may be realized from improvements made to the remaining interior materials; however, it is presently unclear if effective and practical alternate materials are available.

ADDITIONAL WORK

There are a number of planned projects with the C-133 test article, which are continuations of the initial work described in this paper, with the overall goal to better understand and characterize the role of cabin interior materials in postcrash cabin fire survivability. Examination of the effect of fire scenario and material application (e.g., ceiling paneling, sidewalls, carpeting, etc.) on cabin fire hazard development is planned. Also, advanced interior materials to be developed and identified by the National Aeronautics and Space Administration (NASA) will be tested in a realistic manner to determine if significant improvements in survivability can be realized. Finally, the C-133 test article will be utilized in a study designed to determine which small-scale test results give the best correlation with the hazards of burning interior materials during a postcrash cabin fire.

A considerable amount of work has been performed on seat cushion blocking layers beyond that described in this paper. Tests by the FAA have demonstrated that potentially destructive in-flight and ramp fires can be prevented by the application of cushion blocking layers. Because the weight penalty of Vonar PE appears excessive, approximately 2-3 pounds per seat, FAA has entered into an interagency agreement with NASA to develop effective lower weight blocking layer materials. An important finding under this agreement is the apparent effectiveness of aluminized fabrics encasing untreated urethane cushions, resulting in minimal, if any, weight penalty. FAA plans to evaluate this configuration under full-scale postcrash fire conditions in the C-133 test article. Tests completed by the FAA have demonstrated that untreated urethane cushions encased in an aluminized fabric are superior to unlayered FR urethane cushions when subjected to small ignition sources. Other efforts under the interagency agreement include development of a cost/weight computer program, evaluation of the durability of candidate blocking layer materials and large- and small-scale fire tests on candidate materials. Finally, FAA, NASA, Boeing, Lockheed, and McDonnell Douglas are participating in a round-robin evaluation of their respective small-scale fire test methods for seat cushion blocking layers. Eleven material configurations are being evaluated in the round-robin test series as well as under large-scale fire test conditions.

REFERENCES

1. "Engineering and Development Program Plan, Aircraft Cabin Fire Safety," Federal Aviation Administration, FAA Technical Center, Report No. FAA-ED-18-7, June 1980.

2. "Special Study: U.S. Air Carrier Accidents Involving Fire, 1965 through 1974, and Factors Affecting the Statistics," National Transportation Safety Board, Report NTSB-AAS-77-1, February 17, 1977.

3. "Systems Handbook L-1011," TransWorld Airlines, Inc., Technical Services Training, February 1973.

4. Horeff, T. G., "A Crashworthiness Analysis with Emphasis on the Fire Hazard: U.S. and Selected Foreign Turbine Aircraft Accidents, 1964 through 1974," Federal Aviation Administration, Report FAA-RD-75-156, July 1976.

5. National Materials Advisory Board, "Aircraft: Civil and Military, Report of the Committee on Fire Safety Aspects of Polymeric Materials," Publication NMAB 318-6, National Academy of Sciences, Washington, D.C., 1977.

6. Mohler, S. R., "Air Crash Survival: Injuries and Evacuation Toxic Hazards," Aviation, Space and Environmental Medicine, Vol. 46, No. 1, pp. 86-88, January 1975.

7. Birky, M. M., "Hazard Characteristics of Combustion Products in Fires: The State-of-the-Art Review," National Bureau of Standards, Report NBSIR 77-1234, May 1977.

8. "United Air Lines, Inc., Boeing 727, N-7030U, Salt Lake City, Utah, Nov. 11, 1965," Civil Aeronautics Board Aircraft Accident Report SA 388, File No. 1-0032, June 7, 1966, Washington, D.C.

9. "Fire Suppression and Smoke and Fume Protection," Aerospace Industries Association of America, Inc., Report AIA CDP-2, Washington, D.C., 20036, July 1968.

10. Marcy, J. F., "Air Transport Cabin Mockup Fire Experiments," Federal Aviation Administration, NAFEC, Report FAA-RD-70-81, December 1970.

11. Stuckey, R. N., Supkis, D. E., and Price, L. J., "Full-Scale Aircraft Cabin Flammability Tests of Improved Fire-Resistant Materials, NASA, Lyndon B. Johnson Space Center, Report TM X-58141, June 1974.

12. Sarkos, C. P., Spurgeon, J. C., and Nicholas, E. B., "Laboratory Fire Testing of Cabin Materials Used in Commercial Aircraft," Journal of Aircraft, Vol. 16, No. 2, pp 78 - 89, February 1979.

13. "Airworthiness Standards: Transport Category Airplanes," DOT/FAA, Federal Aviation Regulations, Vol. III, Part 25, Transmittal 10, effective May 1, 1972.

14. Heine, D. A., and Brenneman, J. J., "The Cleveland Fire Tests, June 30 and July 1, 1966," Air Lines Pilot Association, Chicago, Ill.

15. Hill, R. G., Johnson, G. R., and Sarkos, C. P., "Postcrash Fuel Fire Hazard Measurements in a Wide-Body Aircraft Cabin," Federal Aviation Administration, NAFEC, Report FAA-NA-79-42, December 1979.

16. Brown, L. J., "Cabin Hazards from a Large External Fuel Fire Adjacent to an Aircraft Fuselage," Federal Aviation Administration, NAFEC, Report FAA-RD-79-65, August 1979.

17. Eklund, T. I., "Preliminary Evaluation of the Effects of Wind and Door Openings on Hazard Development Within a Model Fuselage from an External Pool Fire, Federal Aviation Administration, NAFEC, Letter Report NA-79-1-LR, February 1979.

18. Cooper, L. Y., Harkleroad, M., Quintiere, J., and Rinkinen, W., "An Experimental Study of Upper Hot Layer Stratification in Full-Scale Multiroom Fire Scenarios," Presented at the 20th Joint ASME/AICHE National Heat Transfer Conference, Milwaukee, Wisconsin, Paper 81-HT-9, August 2 - 5, 1981.

19. "Final Report of the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee," Federal Aviation Administration, Volume I, Report FAA-ASF-80-4, June 26, 1980.

20. Morford, R. H., "The Flammability of Neoprene Cushioning Foam," Journal of Fire and Flammability, Vol. 8, pp 279 - 299, July 1977.

21. Court, T. L., Galloway, J. R., and Tobey, R. S., "An Evaluation of the Flammability of Upholstered Furniture Composites by the British Crib Test," Presented at the Sixth International Conference on Fire Safety, Menlo Park, California, January 1981.

22. Spieth, H. H. and Sink, G. T., "Laboratory Fire Hazards Screening Tests - Bart Improved Materials Seat Program," Douglas Aircraft Co., Report MDC-J1817, November 16, 1979.

23. "Aircraft Accident Report: Continental Air Lines, Inc., McDonnell-Douglas DC-10-10, N68045, Los Angeles, California, March 1, 1978," National Transportation Safety Board, Report NTSB-AAR-79-1, January 25, 1979.

24. Guastavino, T. M., Speitel, L. C., and Filipczak, R. A., "The Pyrolysis Toxic Gas Analysis of Aircraft Interior Materials," Federal Aviation Administration, FAA Technical Center, report to be published.

25. Eklund, T. I. and Sarkos, C. P., "The Thermal Impact of External Fuel Fires on Aircraft Fuselages," Journal of Fire and Flammability, Vol. II, pp. 231-240, July 1980.

26. Eklund, T. I., "Pool Fire Radiation through a Door in a Simulated Aircraft Fuselage," Federal Aviation Administration, NAFEC, Report FAA-RD-78-135, December 1978.

27. Spurgeon. J. C., Speitel, L. C., and Feher, R. E., "Thermal Decomposition Products of Aircraft Interior Materials," Federal Aviation Administration, NAFEC, Report FAA-RD-77-20, April 1977.

28. Sarkos, C. P., "Measurement of Toxic Gases and Smoke from Cabin Interior Materials Using the NBS Smoke Chamber and Colorimetric Tubes," Federal Aviation Administration, NAFEC, Report FAA-RD-76-7, March 1976.

29. Spieth, H. H., Gaume, J. G., Luoto, R. E., and Klinck, D. M., "A Combined Hazard Index Fire Test Methodology for Aircraft Cabin Materials," FAA Contract Report by Douglas Aircraft Company, report to be published.

30. Crane, C. R., "Human Tolerance Limit to Elevated Temperature: An Empirical Approach to the Dynamics of Acute Thermal Collapse," Federal Aviation Administration, CAMI, Memorandum Report No. AAC-114-78-2, May 5, 1978.

31. Nicholas, E. B., "Evaluation of Existing Flammability Test Methods by Comparison of the Flammability Characteristics of Interior Materials," Federal Aviation Administration, NAFEC, Report FAA-NA-79-46, March 19S0.

32. Jin, T., "Visibility through Fire Smoke (Part 2. Visibility of Monochromatic Signs through Fire Smoke)," Report of Fire Research Institute of Japan, No. 33, 1971.

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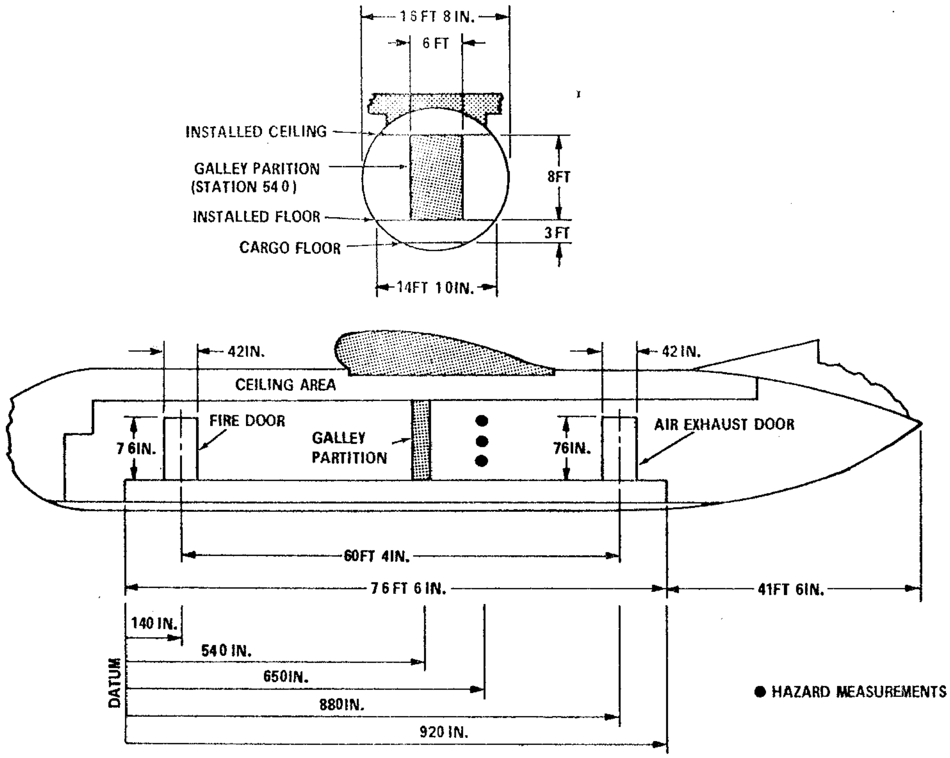


FIGURE 1. SCHEMATIC OF C-133 WIDE BODY CABIN FIRE TEST ARTICLE

FIGURE 2. FULL-SCALE FIRE TEST FACILITY

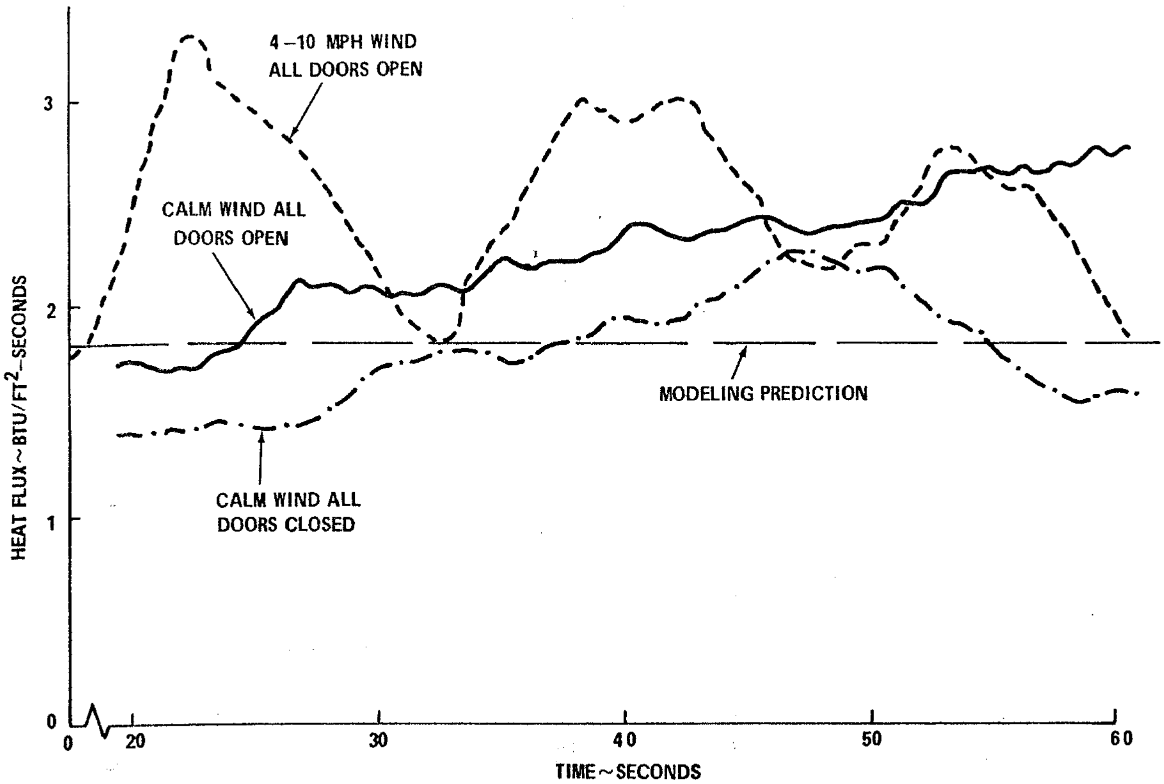


FIGURE 3. DC7 SYMMETRY PLANE HEAT FLUX

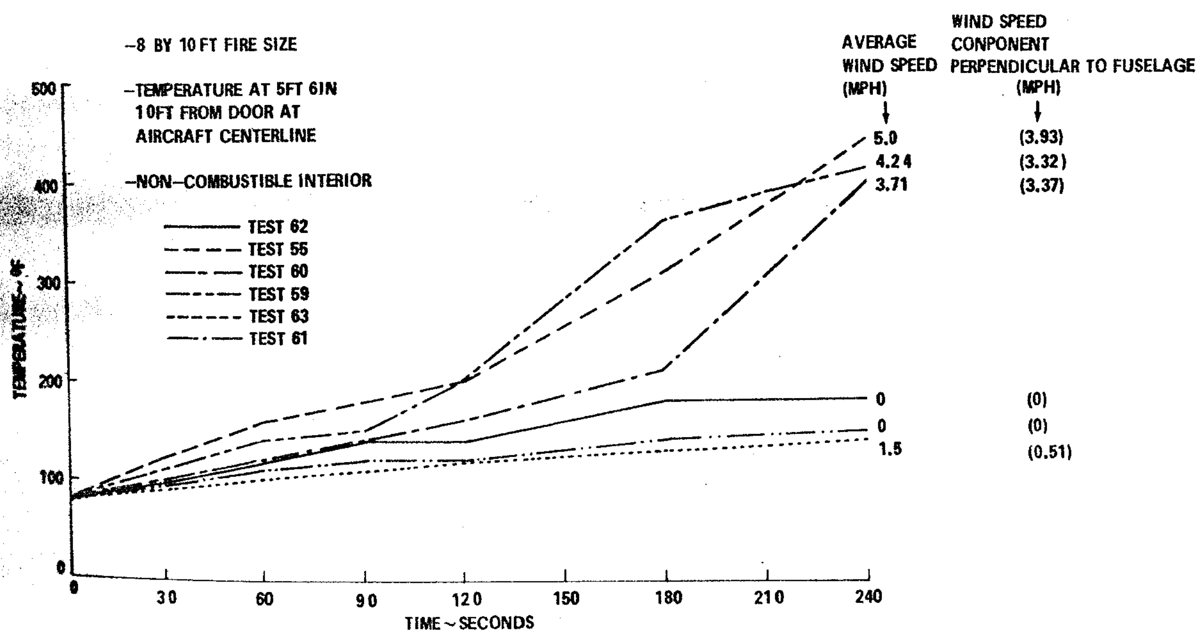


FIGURE 4. EFFECT OF WIND SPEED ON CABIN TEMPERATURE WITH FUSELAGE DOWNWIND OF FIRE

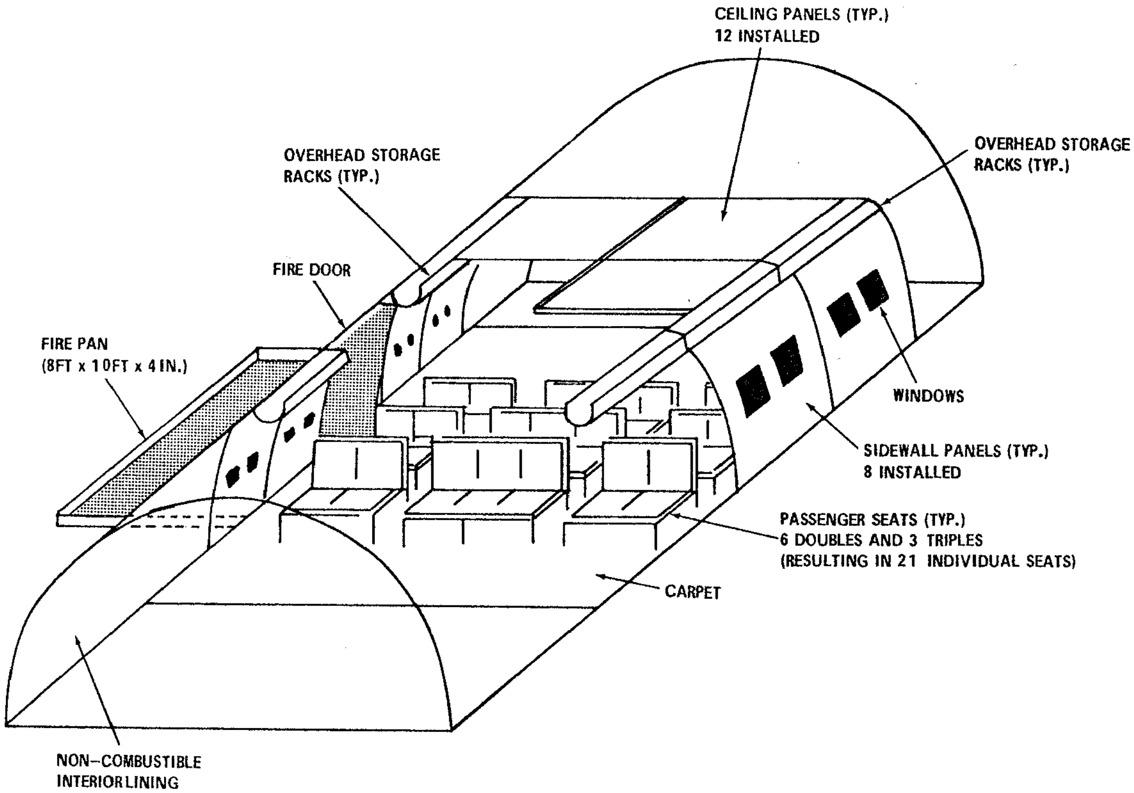
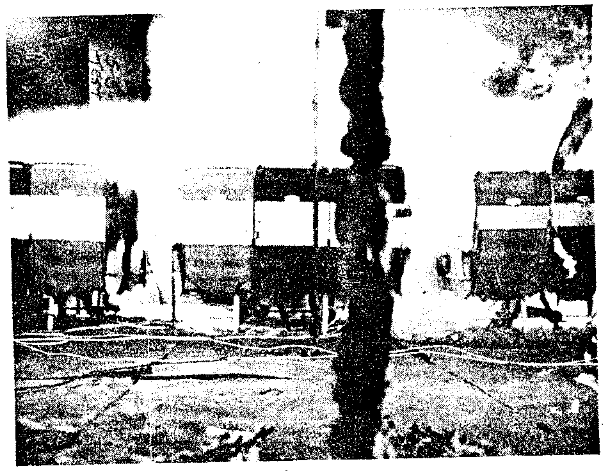


FIGURE 5. INSTALLATION OF WIDE BODY MATERIALS INSIDE C-133 TEST ARTICLE

HEAD STORAGE
; (TYP.)

(TYP.)

L SEATS)



(a) 2:05

(b) 2:10

(c) 2:15

FIGURE 6. PHOTOGRAPHIC DOCUMENTATION OF FLASHOVER

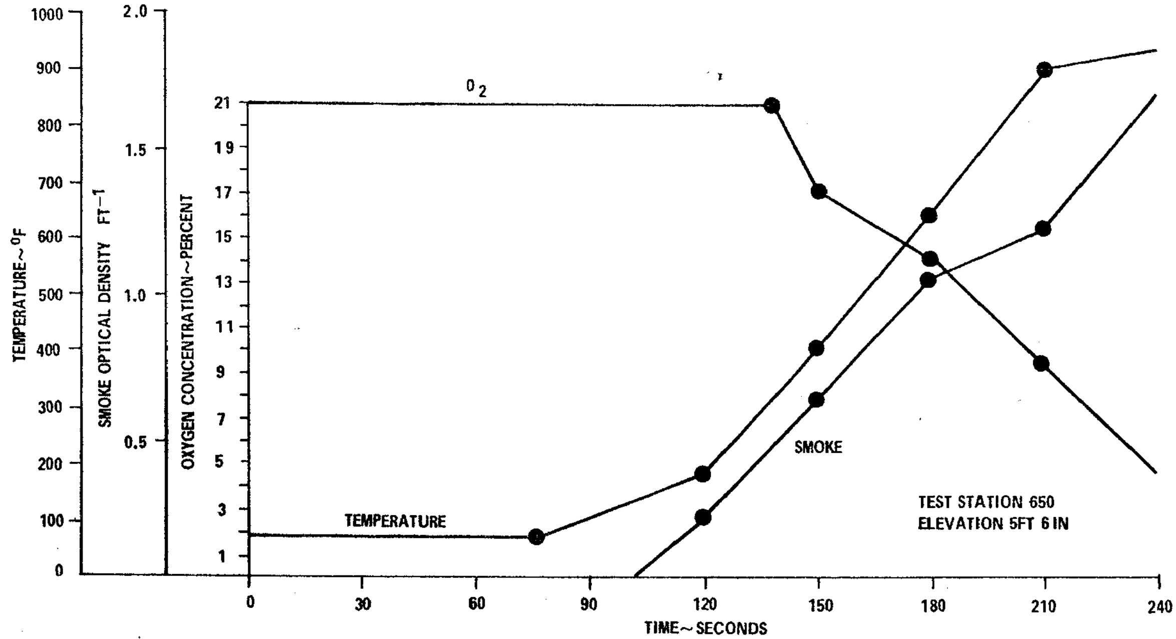
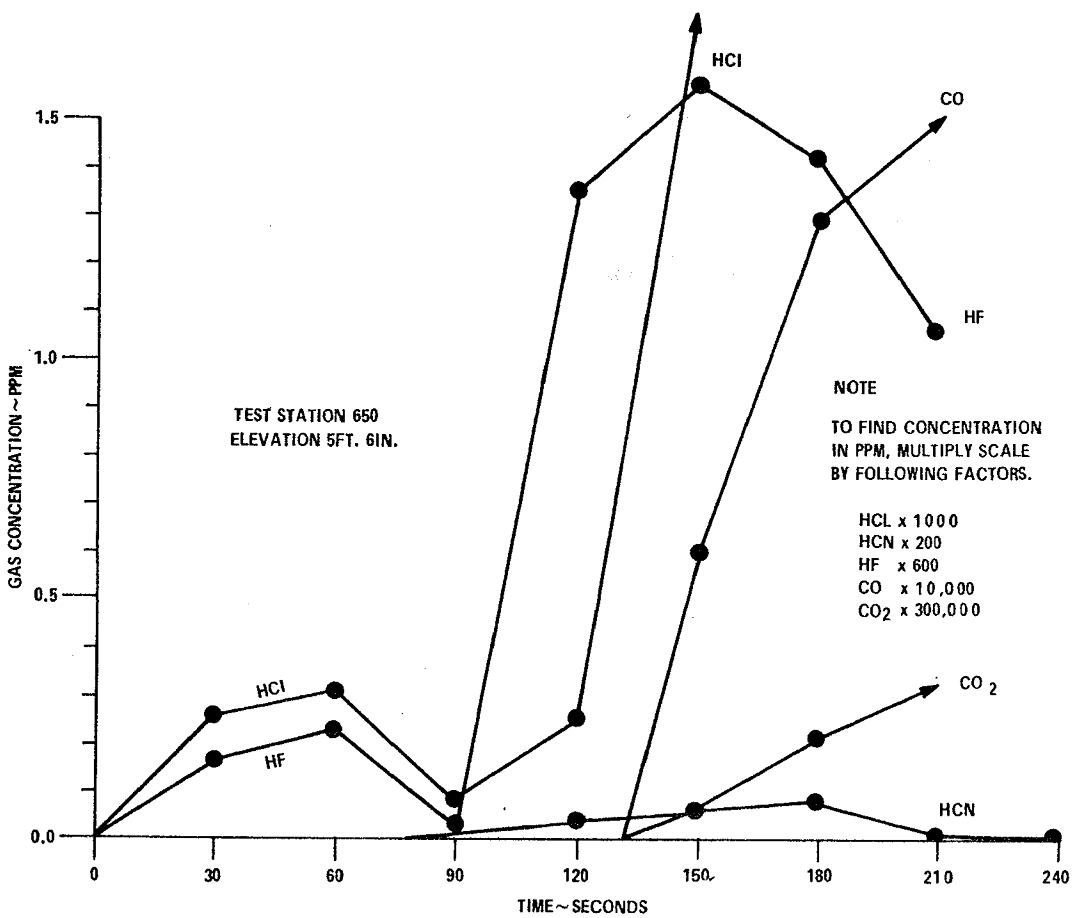


FIGURE 7(a). HAZARDS IN AFT CABIN PRODUCED BY BURNING INTERIOR MATERIALS



FIUGRE 7(b). HAZARDS IN AFT CABIN PRODUCED BY BURNING INTERIOR MATERIALS

1.2
1.0
0.8
0.6
0.4
0.2
0.0
FRACTIONAL EFFECTIVE DOSE

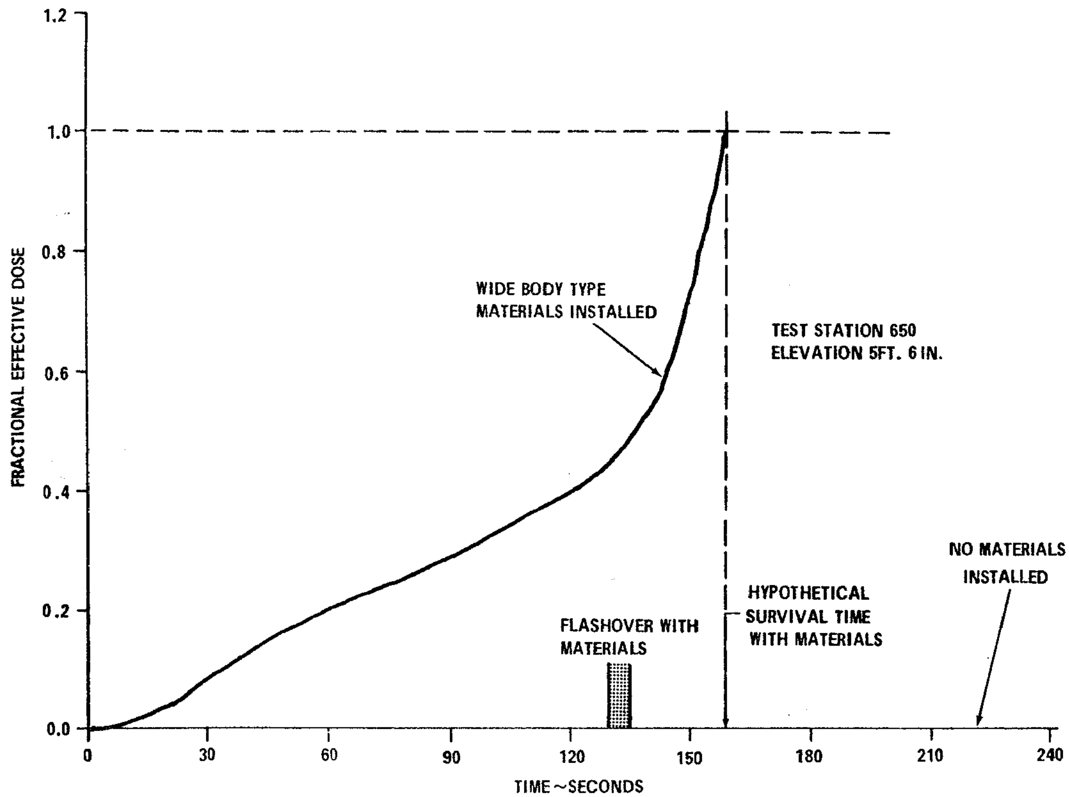


FIGURE 8. HYPOTHETICAL SURVIVAL CURVE IN AFT CABIN

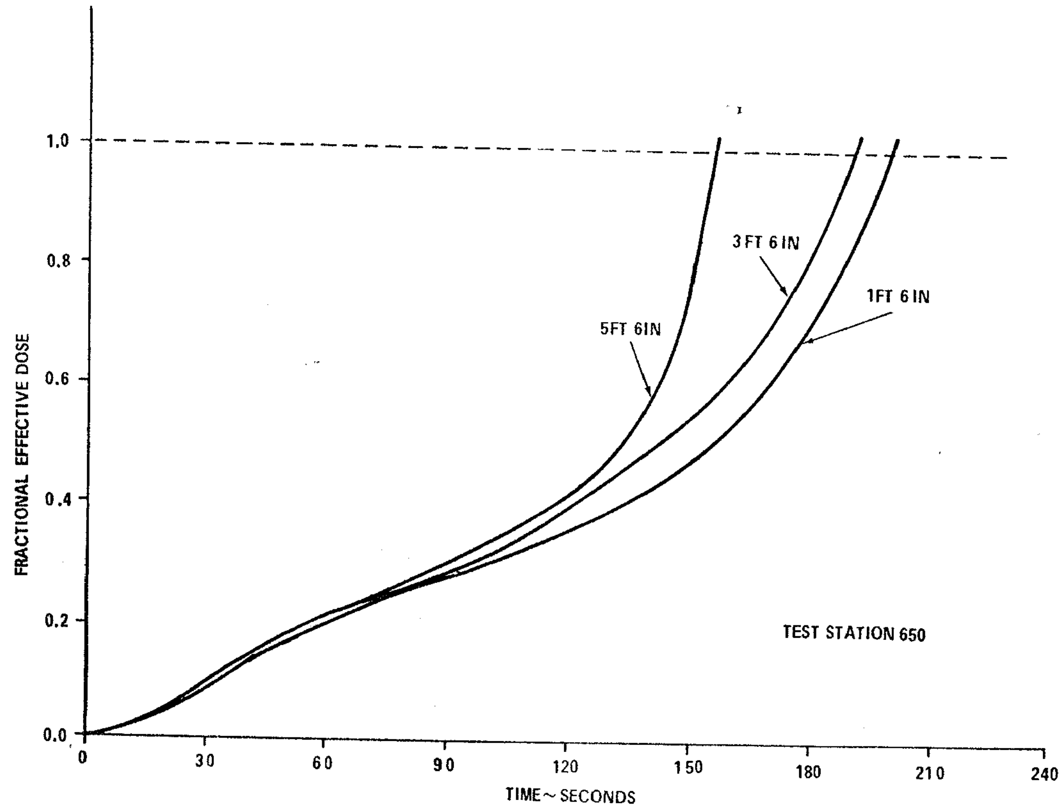


FIGURE 9(a). EFFECT OF ELEVATION ON SURVIVABILITY IN AFT CABIN

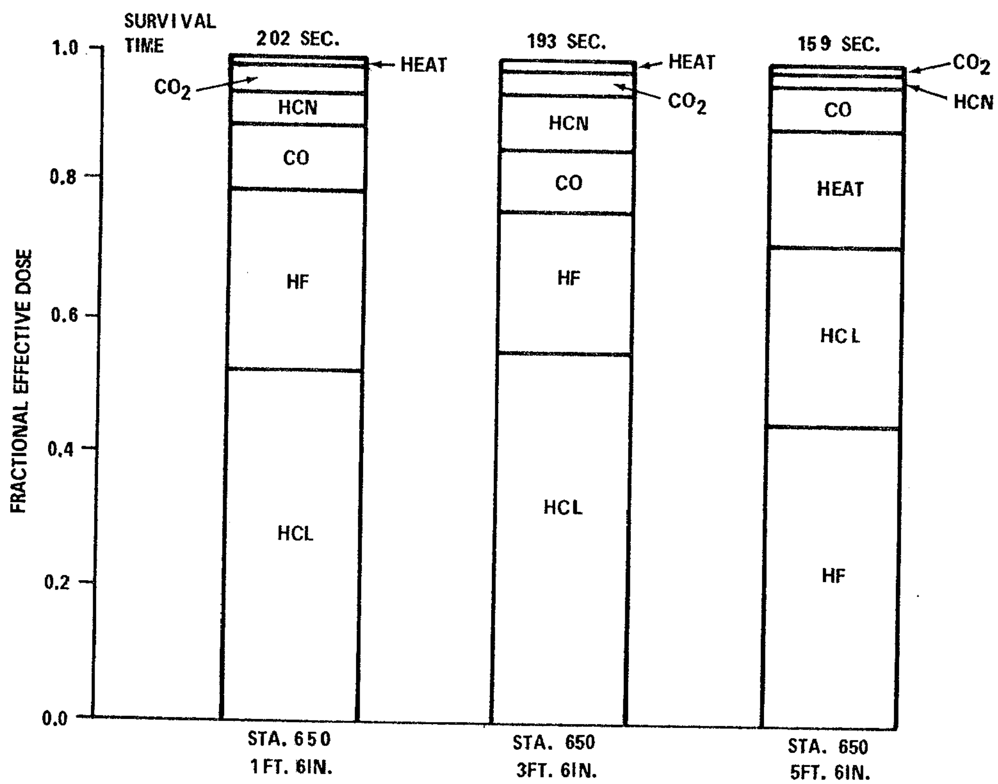
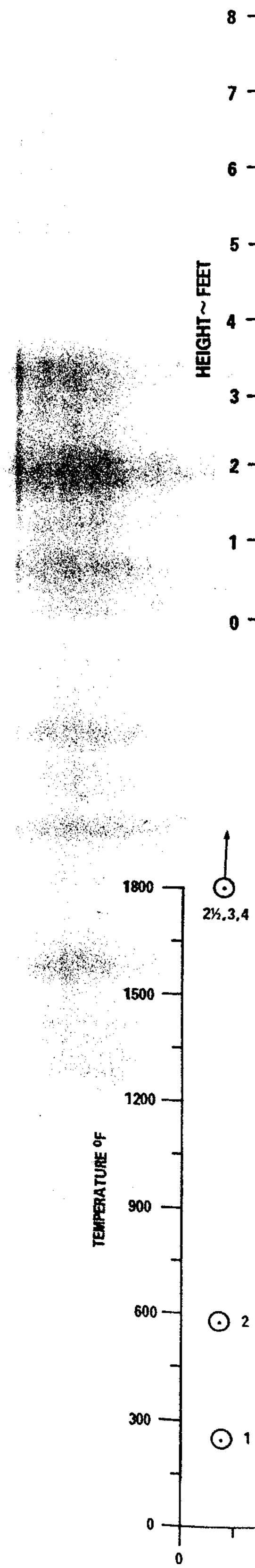


FIGURE 9(b). EFFECT OF ELEVATION ON SURVIVABILITY IN AFT CABIN



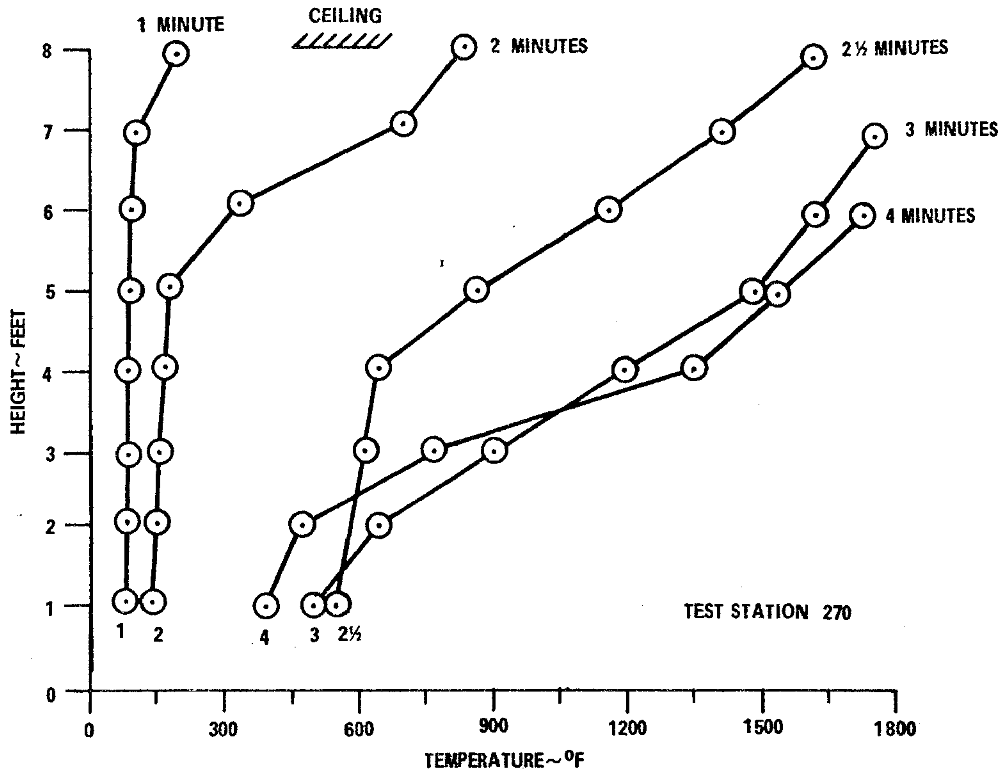


FIGURE 10. HEAT STRATIFICATION IN FORWARD CABIN

240

$\leftarrow CO_2$
HCN

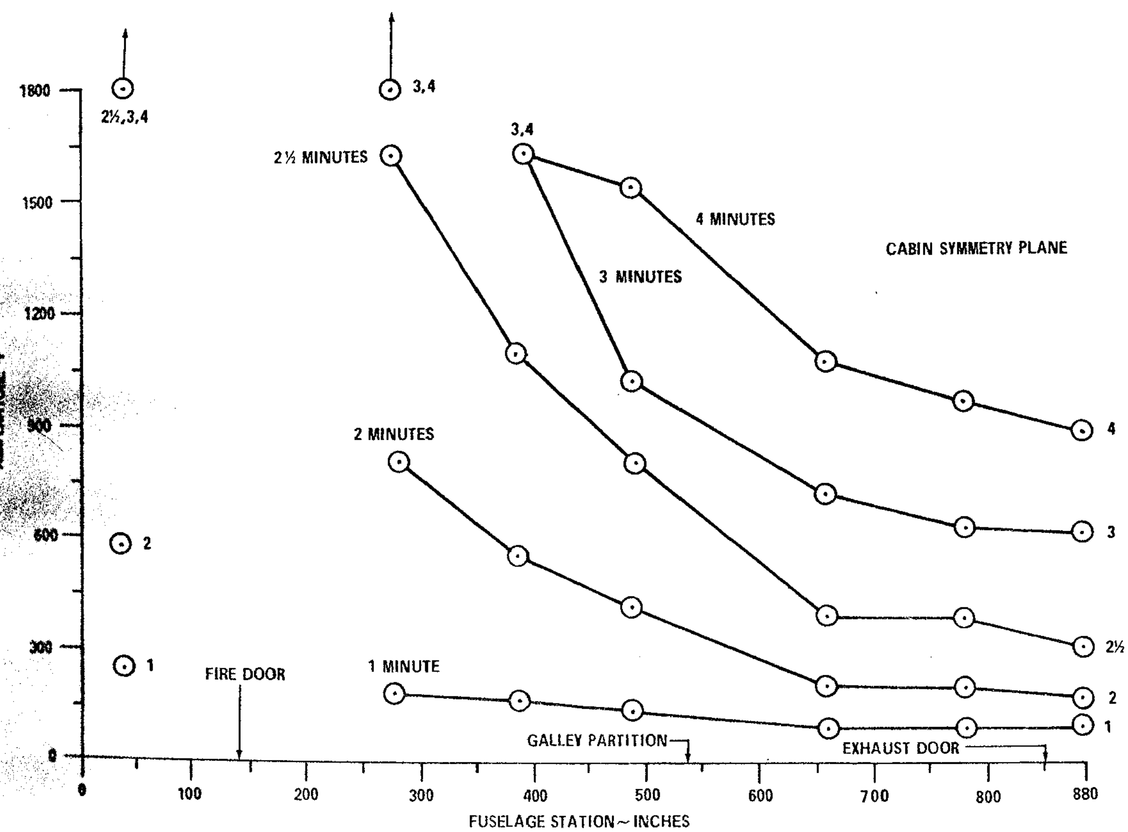


FIGURE 11. LONGITUDINAL TEMPERATURE PROFILE AT CEILING

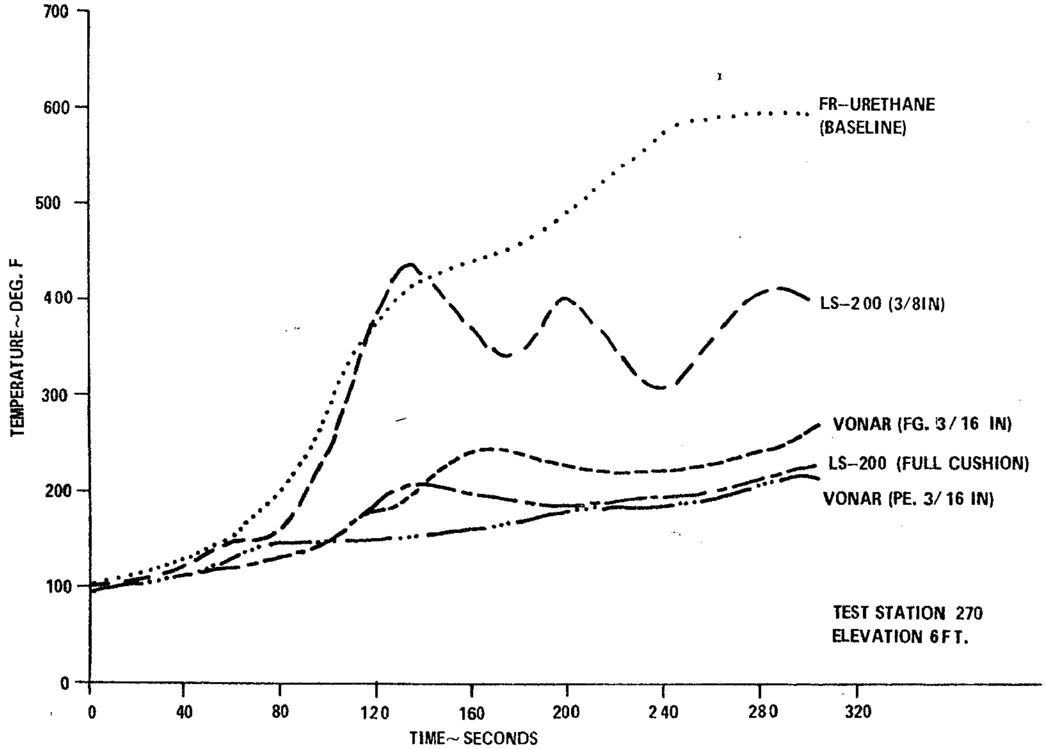


FIGURE 12. BLOCKING LAYER RESULTS ON DOUBLE SEAT CUSHIONING MOUNTED ON METAL FRAME

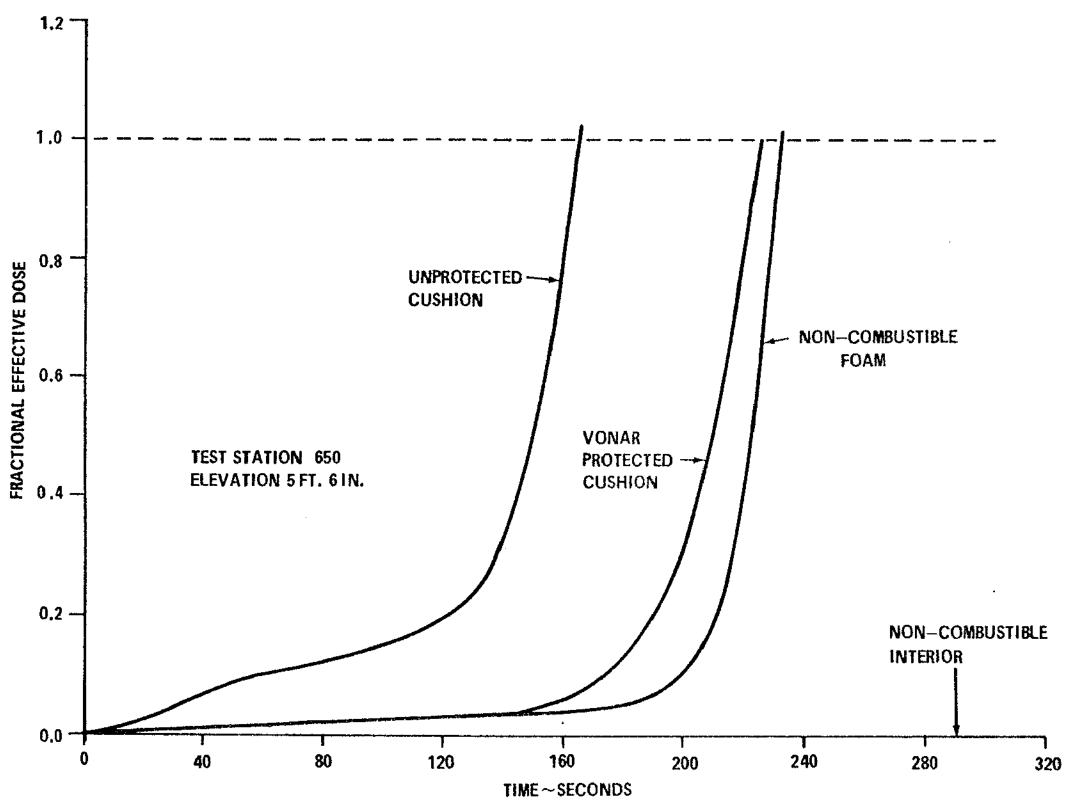


FIGURE 13. EFFECT OF CUSHIONING PROTECTION AND MATERIALS ON CALCULATED SURVIVAL TIME

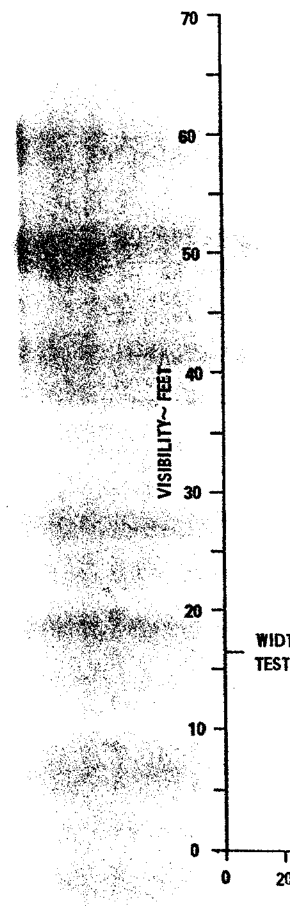


FIGURE 1

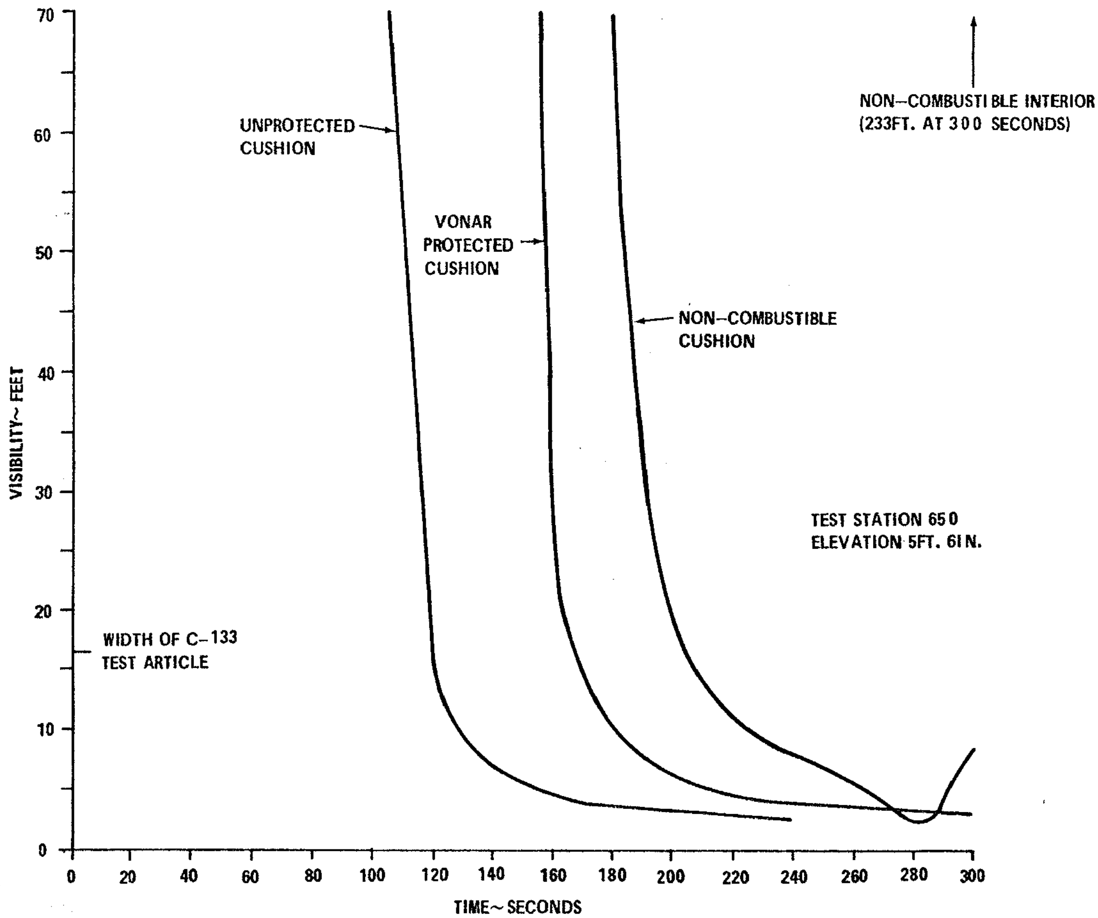


FIGURE 14. EFFECT OF CUSHIONING PROTECTION AND MATERIALS ON CALCULATED VISIBILITY THROUGH SMOKE